AEDC-TR-86-46

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Determination of Installed Thermocouple Response

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December 1986

Final Report for Period January 1985 – February 1986

Approved for public release; distribution unlimited.

ARNOLD ENGINEERING DEVELOPMENT CENTER
ARNOLD AIR FORCE STATION, TENNESSEE
AIR FORCE SYSTEMS COMMAND
UNITED STATES AIR FORCE

APPROVAL STATEMENT

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UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AEDC-TR-86-46	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Analysis and Measurement Services Corporation 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State and ZIP Code) 4706 Papermill Road Knoxville, TN 37909	7b. ADDRESS (City, State and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Arnold Engineering Development Center 8b. OFFICE SYMBOL (If applicable) DOT	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F40600-85-C-0006
8c. ADDRESS (City, State and ZIP Code) Air Force Systems Command Arnold Air Force Station, TN 37389-5000	10. SOURCE OF FUNDING NOS. PROGRAM ELEMENT NO.: 65807F PROJECT NO.: TASK NO.: WORK UNIT NO.:
11. TITLE (Include Security Classification) Determination of Installed Thermocouple Response	
12. PERSONAL AUTHOR(S) Hasehemian, H.M., Analysis and Measurement Services Corp.	
13a. TYPE OF REPORT: Final 13b. TIME COVERED: FROM 1/28/85 TO 2/28/86	14. DATE OF REPORT (Yr., Mo., Day): December 1986 15. PAGE COUNT: 77
16. SUPPLEMENTARY NOTATION Available in Defense Technical Information Center (DTIC).	

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	
20	13		thermocouple; step response; frequency response; response time; time constant; installed response time

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The validity of the Loop Current Step Response method was established for type J, K, E, and T thermocouples. Prototype equipment configurations and signal processing methods were tested to determine the features needed in a commercial test instrument. This work completes the proof testing of the in-situ method for response time testing of thermocouples as installed in operating processes or test facilities.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☒ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION Unclassified
22a. NAME OF RESPONSIBLE INDIVIDUAL William O. Cole	22b. TELEPHONE NUMBER (Include Area Code): (615) 454-7813 22c. OFFICE SYMBOL: DOS

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE.

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SECURITY CLASSIFICATION OF THIS PAGE

PREFACE

The work reported herein was conducted by Analysis and Measurement Services Corporation for Arnold Engineering Development Center/DOT, Air Force Systems Command, Arnold Air Force Station, Tennessee, during the period January 28, 1985 to February 28, 1986, under contract number F40600-85-C0006. The Air Force Project Manager was Mr. Robert W. Smith, AEDC/DOT; the report was written by H.. M. Hashemian, Analysis and Measurement Services Corporation.

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1. INTRODUCTION

The Loop Current Step Response (LCSR) method for in-situ response time testing of thermocouples was investigated. The LCSR method has been used previously for platinum resistance thermometers and thermocouples. Extensive laboratory and field testing experience has been accumulated for resistance thermometers but only limited experience with type K insulated junction, sheathed thermocouples has been accumulated. Furthermore, very little prior work has been done on test equipment and on validity assessment for the method.

A program of testing and analysis was performed to establish testability and accuracy of LCSR testing for type J, K, E and T thermocouples and to optimize the test equipment design for this testing. This program is intended to satisfy the requirements of the U.S. Air Force as specified in Air Force Topic 213 in Small Business Innovation Research Program Solicitation 85-1.

2. THE LOOP CURRENT STEP RESPONSE METHOD

Frequency response and time response characterization is potentially important for most temperature sensors. Classical testing of thermocouples involves plunging them into a stirred water bath in a laboratory (Figure 2.1). This provides information only about the response of the thermocouple under those particular test conditions and does not provide information about the response at process or test facility operating conditions where the sensor is to be used. Since the response is greatly affected by process conditions, a technique is required to perform response measurements on an installed thermocouple (an in-situ test). The medium around the sensor and its temperature and flow rate are among the process conditions which have a significant effect on sensor response time.

A new method called the Loop Current Step Response (LCSR) method has been developed for in-situ response time measurement of thermocouples and resistance thermometers.[1-5] The significance of this method is that it can be used to measure the frequency response and time response of thermocouples and resistance thermometers while they are installed in an operating process or test facility. This provides a means for measuring the sensor response for actual operating conditions and installation details. The suitability of this technique has

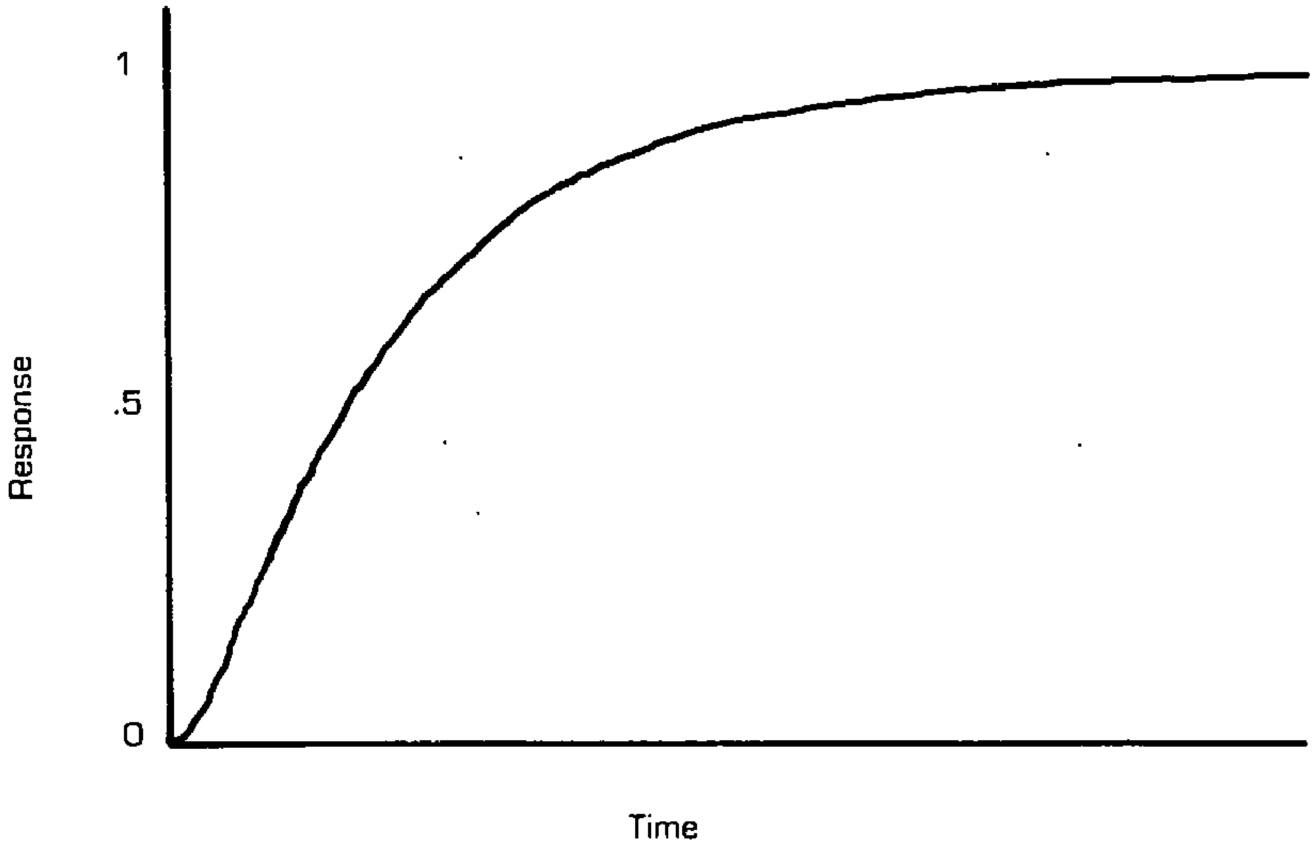


Figure 2.1: Response of a Thermocouple to a Step Change in Surrounding Temperature.

been verified by laboratory experience with resistance thermometers and type K thermocouples as well as in-process testing for platinum resistance thermometers.

The LCSR method for thermocouples involves passing an electric current through the sensor leads, which causes the sensor to settle at a temperature a few degrees above ambient temperature. Then the heating current is stopped, and the output from the sensor is monitored as it cools (Figure 2.2). The output indicates the response of the sensor to changes in internal heating, but the required information is the response of the sensor to changes in the monitored temperature. Hence an analytical method has been developed for transforming the LCSR test data into the response that would be obtained following a change in the monitored temperature.

It has been shown[3] that the transfer function which related sensor output to process temperature variations has the following form:

$$G_1(s) = \frac{K_1}{(1 + \tau_1 s)(1 + \tau_2 s). . .} \tag{2.1}$$

where

$G_1(s) = \delta E(s)/\delta T(s)$

$\delta E(s)$ = Laplace transform of the change in sensor output.

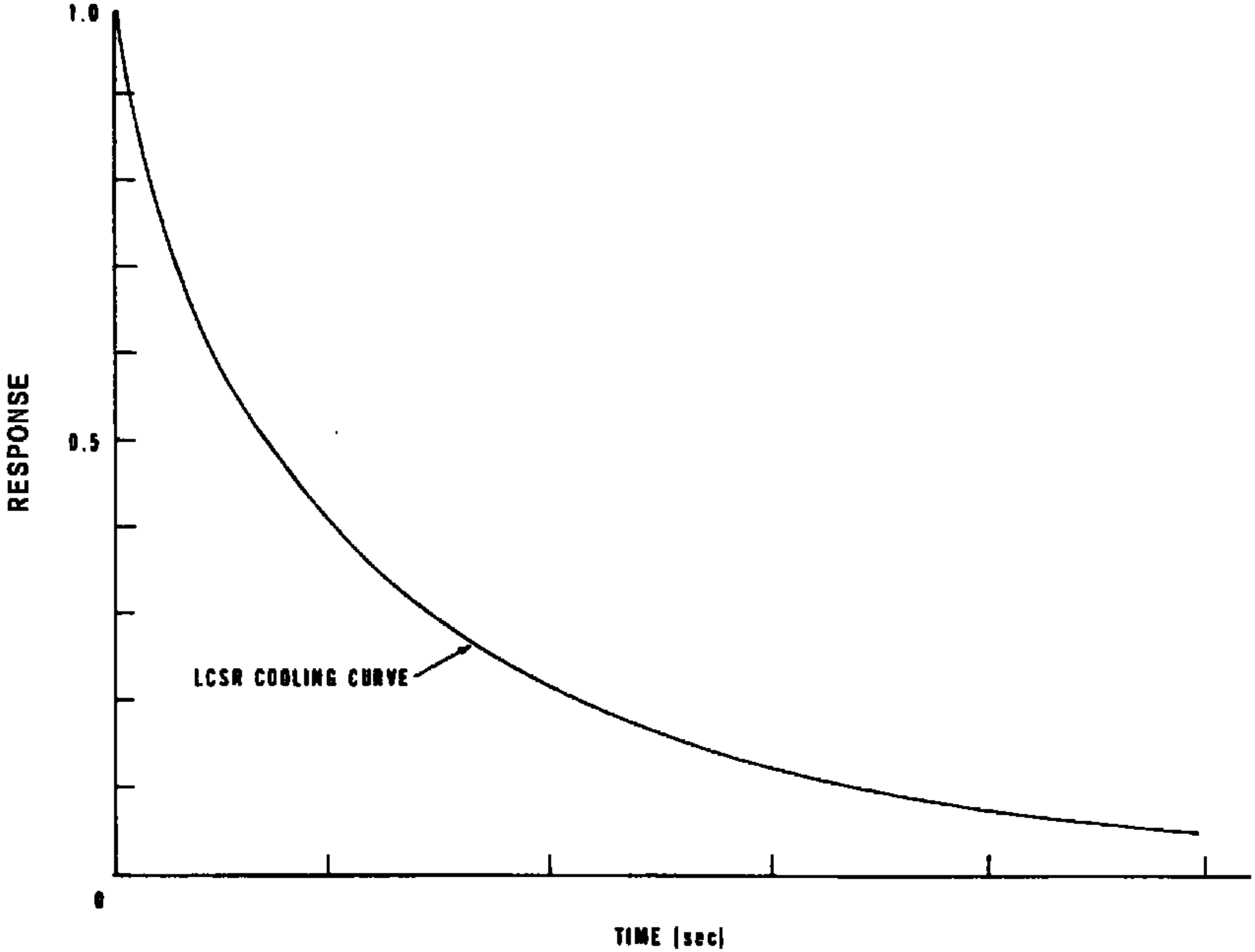


Figure 2.2: Output of a Thermocouple in a LCSR Test.

$\delta T(s)$ = Laplace transform of the change in monitored temperature.

τ_i = Modal time constant for mode i.

K_1 = A constant.

It has also been shown[3] that the transfer function which relates sensor output to changes in internal heating in the sensor has the following form:

$$G_2(s) = \frac{K_2(1 + r_1 s)(1 + r_2 s) \ldots}{(1 + \tau_1 s)(1 + \tau_2 s) \ldots} \tag{2.2}$$

where

$G_2(s) = \delta E(s)/\delta P(s)$

$\delta P(s)$ = Change in power at the sensing element.

$-1/r_i$ = Zero of transfer function.

K_2 = A constant.

Key points are that the τ_i are the same in both transfer functions and that only the first few modes (τ_i and r_i) are significant in determining the sensor dynamics. This leads to the following important conclusion:

A test which uses internal heating as an input provides transient data which contains information about the modal time constants (τ_i) and these modal time constants provide all of the information needed to determine the transfer function of interest (G_1).

These observations led to the LCSR test development. For a step change in heating power applied to the sensing element, the time response has the form:

$$E(t) = A_o + A_1 e^{-t/\tau_1} + A_2 e^{-t/\tau_2} + \ldots \tag{2.3}$$

The LCSR test for thermocouples involves monitoring the response following cessation of heating caused by passing a current through the sensor leads. Analysis of the data (by methods such as exponential peeling or curve fitting) provides the required modal time constants (τ_i). The values for the modal time constants and Equation 2.1 provide the transfer function which may then be used to provide any dynamic characterization of interest for the sensor (i.e. frequency response, step response or overall time constant).

Instrumentation for response time testing of thermocouples is shown in a simplified schematic in Figure 2.3. The basic concept has been proven, but several instrumentation problems occur in LCSR testing of thermocouples. These are:

1. <u>Joule Heating and Peltier Effect.</u> The total heating effect associated with electric current flow through thermocouple wires has two components: Joule heating (proportional to current squared and distributed along the whole length of the wire) and the Peltier effect. Peltier heating or cooling is proportional to current and is concentrated at the measuring junction. The Peltier component can cause a problem if DC current is used, because the temperature gradient along the wire that accompanies the Peltier effect causes a temperature transient at the measuring junction upon cessation of the current

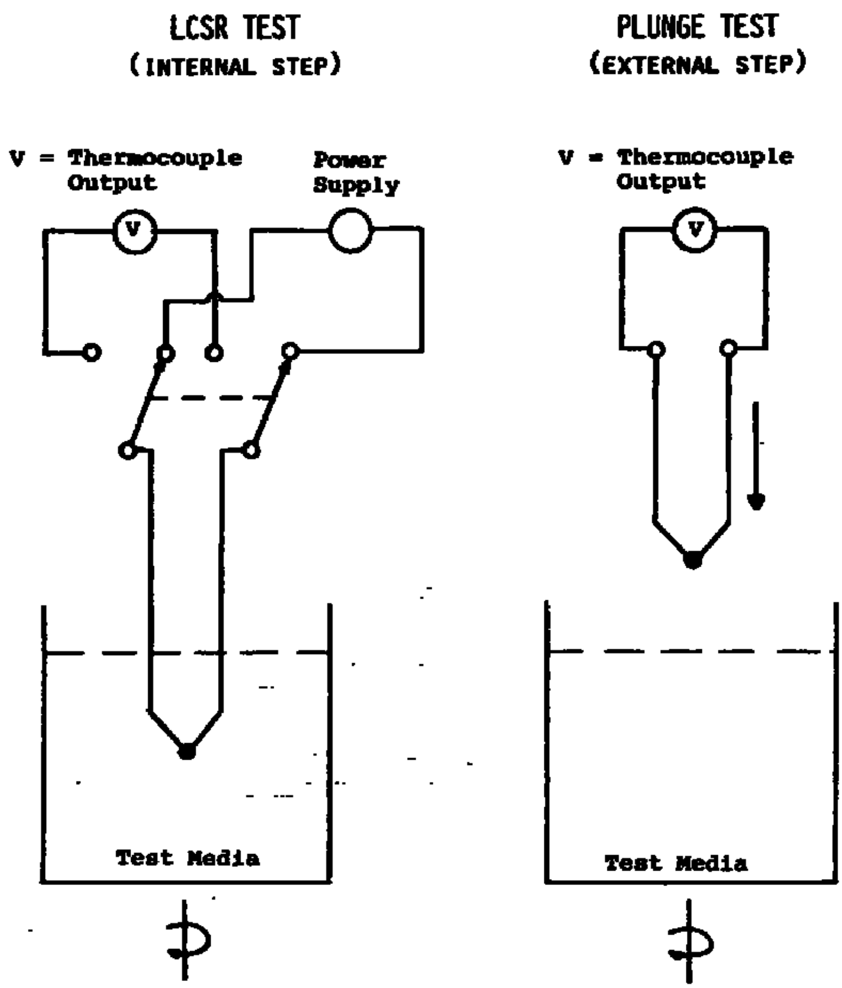


Figure 2.3: Instrumentation for Thermocouple Response Time Testing.

that is unrelated to the radial heat transfer to the surrounding medium. To eliminate the Peltier effect, AC current may be used for thermocouple heating. However, Peltier heating or cooling may provide enhanced capability in testing since it is localized at the junction and should be evaluated experimentally.

2. Magnetic Effects. Thermocouples with ferromagnetic wires experience magnetic effects which interfere with response time measurement by the LCSR method. This problem can be resolved by using a special cut-off system for fast thermocouples with ferromagnetic wires.

3. Resistance of Extension Wire. The electrical resistance of extension wire is usually very small and is distributed along the whole length of the wire. This requires heating currents of several amperes to achieve adequate heating unless special care is exercised in improving signal quality so that lower currents can be used.

4. Connector Effects. Connectors, terminal blocks, etc. in the thermoelectric circuit create potential thermoelectric inhomogeneities which can cause false signals in a LCSR test. The simplest solution is to eliminate all such connectors from the thermoelectric circuit. However, this is not always possible and tests should be performed to evaluate errors caused by connectors and to determine connector selections which minimize errors.

5. Electrical Hazard/Signal Quality Tradeoff. Larger heating currents give higher temperature rises and higher signal levels in LCSR transients. However, higher applied voltages increase the electrical hazard. Earlier work has tolerated potentially hazardous voltages and has depended on appropriate caution by the operator. Because of the need to avoid hazardous voltages in this project, special consideration was given to the readout electronics and the heat sink/conductor in order to optimize the signal-to-noise ratio.

3. THERMOCOUPLE CHARACTERISTICS

It is necessary to understand the operating principles of thermocouples fully in order to develop effective test methods. The basic principle is that an open-circuit voltage is produced by a pair of metallic wires which experience temperature gradients (Figure 3.1). This may be expressed analytically as:

$$V = \int_0^L S_{ab} \frac{\partial T}{\partial l} dl \qquad (3.1)$$

where

V = open-circuit voltage

L = length of thermocouple wires

S_{ab} = relative Seebeck coefficient for wires made of materials, a and b

T = temperature

l = position along the wires

The relative Seebeck coefficient for a pair of materials is generally a function of temperature. Equation 3.1 may also be written as:

$$V = \int_{T_1}^{T_2} S_{ab} \, dT \qquad (3.2)$$

Consequently, the open-circuit voltage may be determined

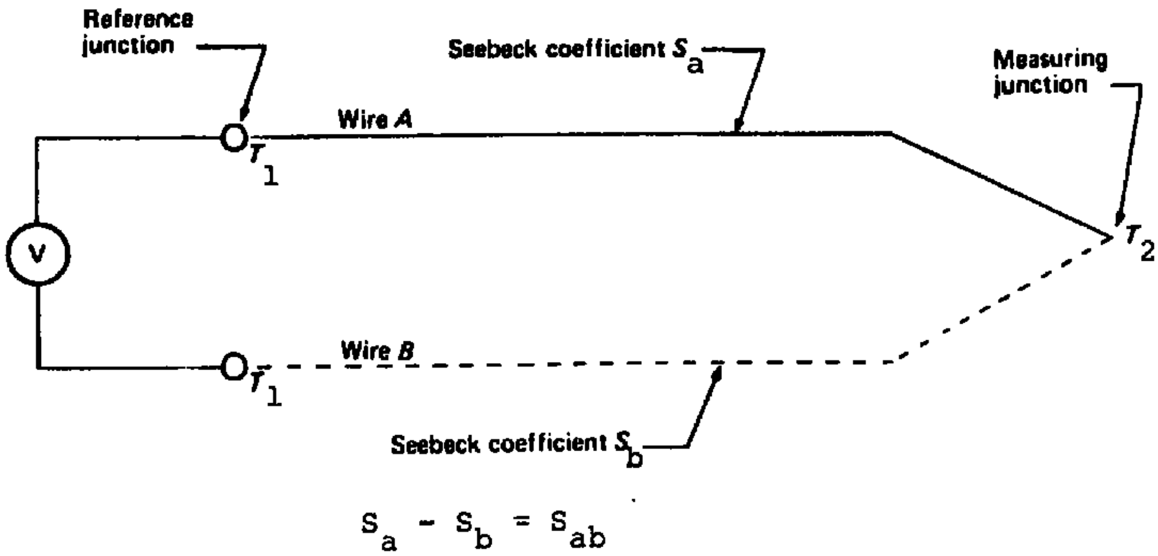


Figure 3.1: A Basic Thermocouple Circuit.

uniquely for various values of T_1 and T_2. Usually, T_1 is fixed at the ice point and tables are developed for V versus T_2. This is the basis for standard thermocouple tables.

Thermocouple performance can be affected if the circuit contains sections with materials having Seebeck coefficients different than S_{ab}. This can occur because of installation effects (connectors) or aging (metallurgical or chemical changes). For example, consider a thermocouple with changes in section L_1 to L_2 which cause the Seebeck coefficient to change from the S_{ab} to $S_{a'b'}$ (Figure 3.2). Then

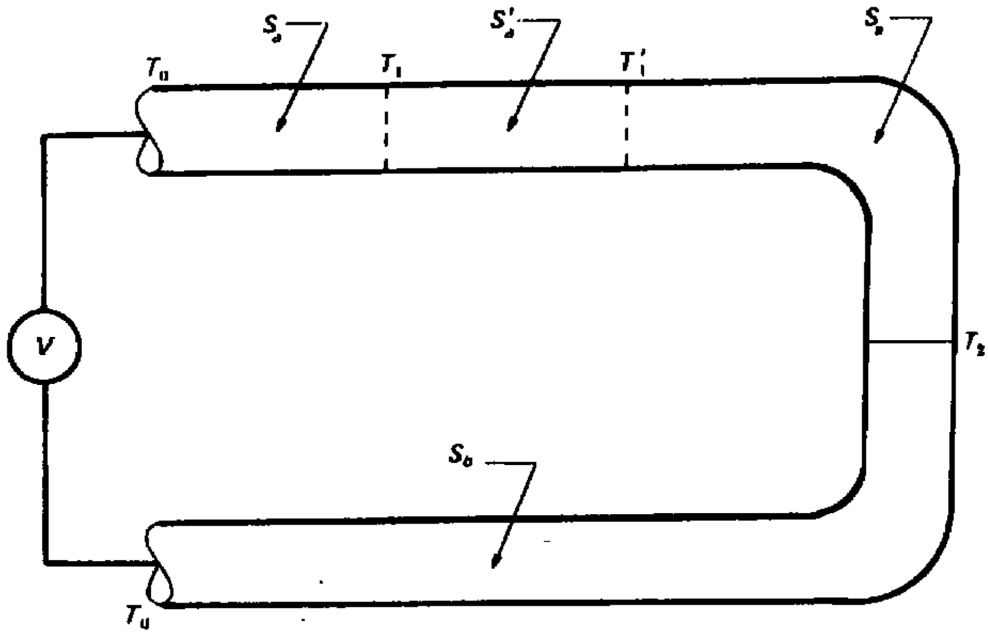
$$V = \int_0^{L_1} S_{ab} \frac{\partial T}{\partial l}\, dl + \int_{L_1}^{L_2} S_{a'b'} \frac{\partial T}{\partial l}\, dl + \int_{L_2}^{L} S_{ab} \frac{\partial T}{\partial l}\, dl \qquad (3.3)$$

or

$$V = \int_0^{L} S_{ab} \frac{\partial T}{\partial l}\, dl + \int_{L_1}^{L_2} (S_{a'b'} - S_{ab}) \frac{\partial T}{\partial l}\, dl \qquad (3.4)$$

The first term in Equation 3.4 is the expression for the unaltered thermocouple circuit. The second term gives the voltage contribution of the altered section. Equation 3.4 shows that the contribution of the second term is non-zero only if the temperature gradient ($\partial T/\partial l$) is non-zero in L_1 to L_2.

The influence of thermoelectric inhomogenieties is important in normal temperature measurements and in LCSR testing. It is



$$V = S_{ab}(T_2 - T_0) + S_{a'a}\Delta T$$

Figure 3.2: A Thermocouple with an Inhomogeneous Section.

the main cause of measurement errors with thermocouples. In LCSR testing, temperature gradients may be introduced at inhomogenieties by the Joule heating even though they may not exist during normal operation. Consequently, special attention must be given to inhomogenieties (intentional such as connectors or unintentional).

The ability of a thermocouple to measure temperature depends entirely on the Seebeck effect. An additional thermoelectric effect, the Peltier effect, enters into LCSR testing. The Peltier effect is localized heating or cooling of a thermocouple junction caused by passage of a direct current through a thermoelectric circuit. The polarity of the applied voltage determines whether heating or cooling occurs. This effect is in addition to Joule heating due to passage of current through the sensor. In LCSR testing, Peltier heating or cooling may be introduced by using direct current or avoided by using alternating current.

Thermocouples may be built in a number of configurations. The most common are (Figure 3.3):

- Sheathed, insulated
- Sheathed, grounded
- Bare, ungrounded
- Bare, grounded

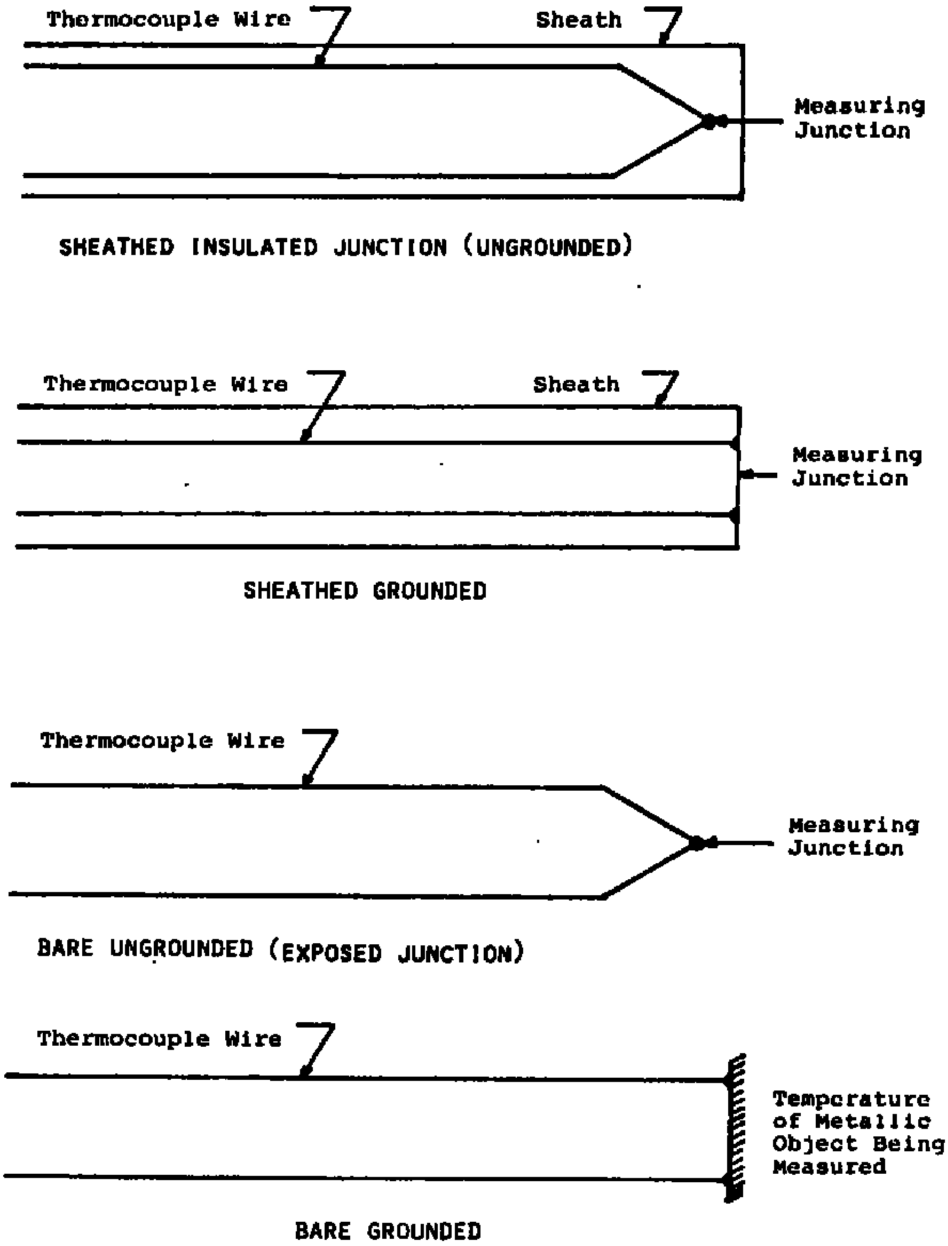


Figure 3.3: Common Thermocouple Configurations

All four configurations permit temperature measurements using the same basic thermoelectric principles. They provide different challenges in developing effective LCSR methods. In particular, the grounded configurations give different electrical and thermal pathways for exchange between the sensor and the environment. These must be addressed in LCSR testing on these configurations.

4. LCSR TEST EQUIPMENT

The basic LCSR test instrument for thermocouples is shown in Figure 4.1. The main areas of concern are the power supply and the heat sink-connectors.

The choices for the power supply are:

A. High frequency (>60 Hz) AC
B. Low frequency (60 Hz) AC
C. DC

High frequency AC is useful for testing very fast thermocouples (with time constants in the milliseconds range) without employing the Peltier effect. Use of high frequency insures that the heating and cooling cancel. For slower thermocouples, a lower frequency power supply is adequate. The Peltier effect associated with a DC power supply introduces a localized temperature change at the junction which may be a benefit or a disadvantage for LCSR testing.

In this project, two test instruments were operated and compared. One used a 60 Hz power supply and the other used a DC power supply.

The heat sink-connector must provide a constant temperature reference junction during the LCSR test. There are two ways to

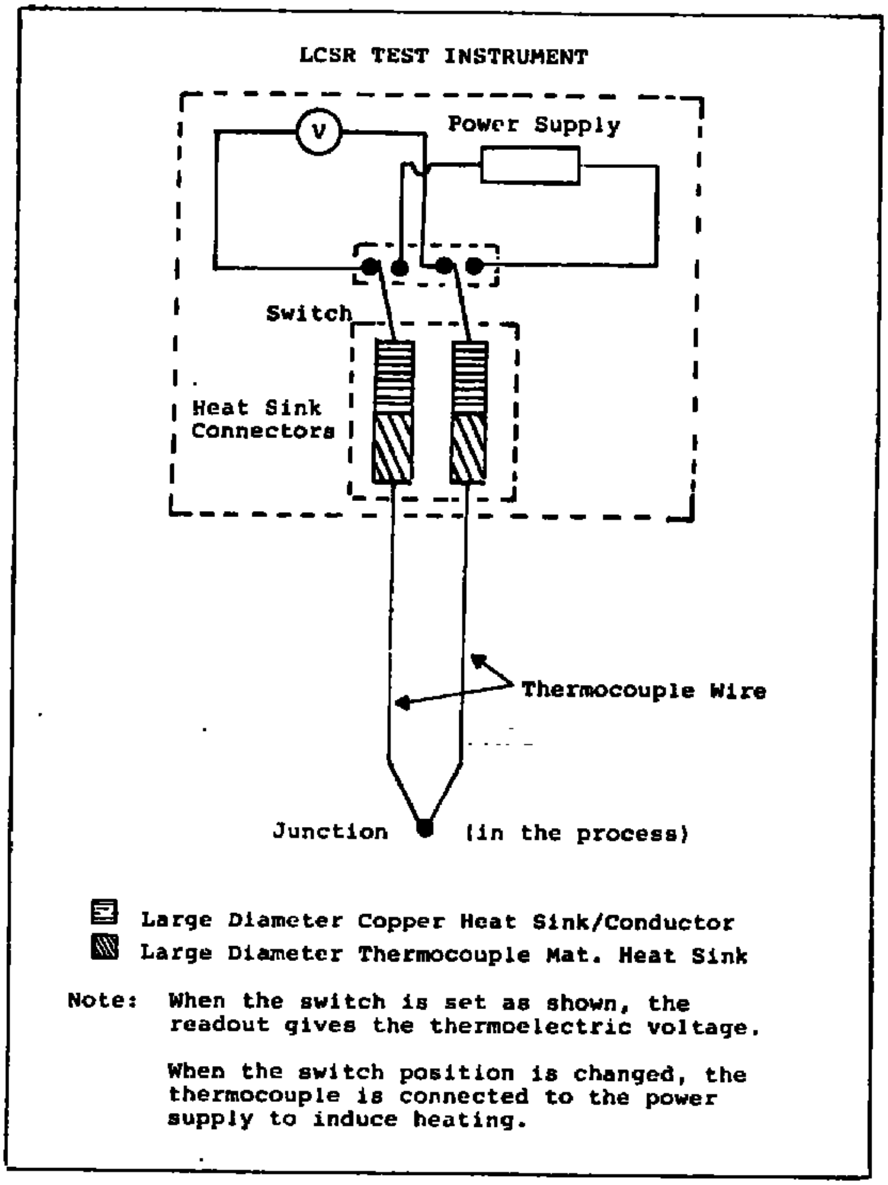


Figure 4.1: Basic LCSR Test Instrument for Thermocouples.

accomplish this. One is to make conductors in the section where the thermocouple metal-to-copper transition occurs out of large diameter pieces so that the resistance and Joule heating are low. The other approach is to remove the junction from the circuit during the heating phase.

5. EXPERIMENTAL PROGRAM

5.1. Testing in Water

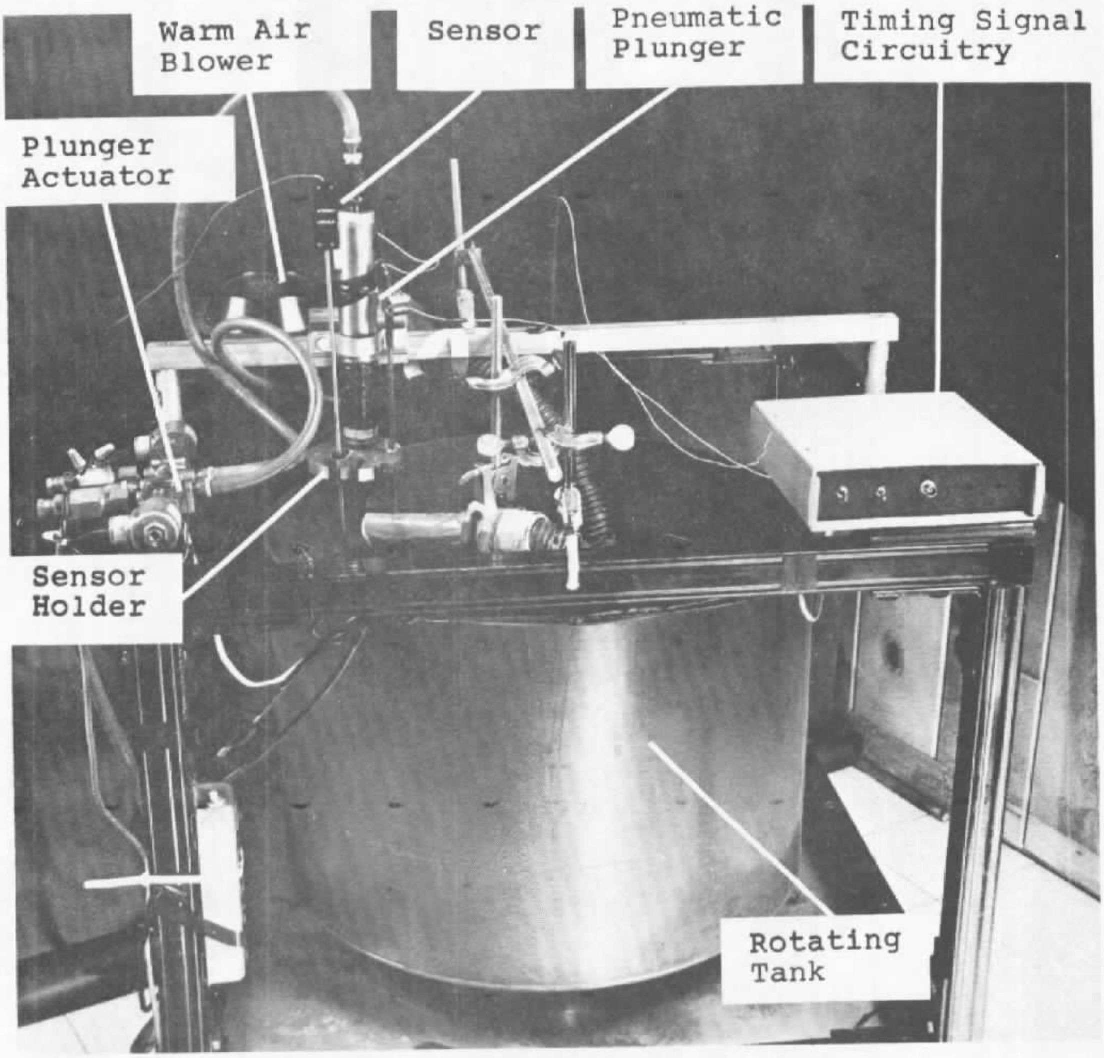
LCSR testing had two main purposes: to determine whether good quality data could be obtained for all thermocouple types of interest and to determine the validity of sensor time response estimates obtained from LCSR testing. The tests were performed with the thermocouples inserted in water. The facility consisted of a rotating tank with rotational speed selected to give a water velocity of approximately 1 meter/sec. The facility is shown in Figure 5.1. The data acquisition system is shown in Figure 5.2. A listing of the equipment used is given in Table 5.1. A simplified schematic of the LCSR Test Instrument is presented in Figure 5.3. This instrument is referred to as the ETC-1. The same instrument was used with an AC Power Supply for AC heating and with a DC power supply for DC heating.

Thermocouples were installed in the flowing water and LCSR tests were performed. The procedure was as follows:

1. Wait for the thermocouple signal to reach steady state.

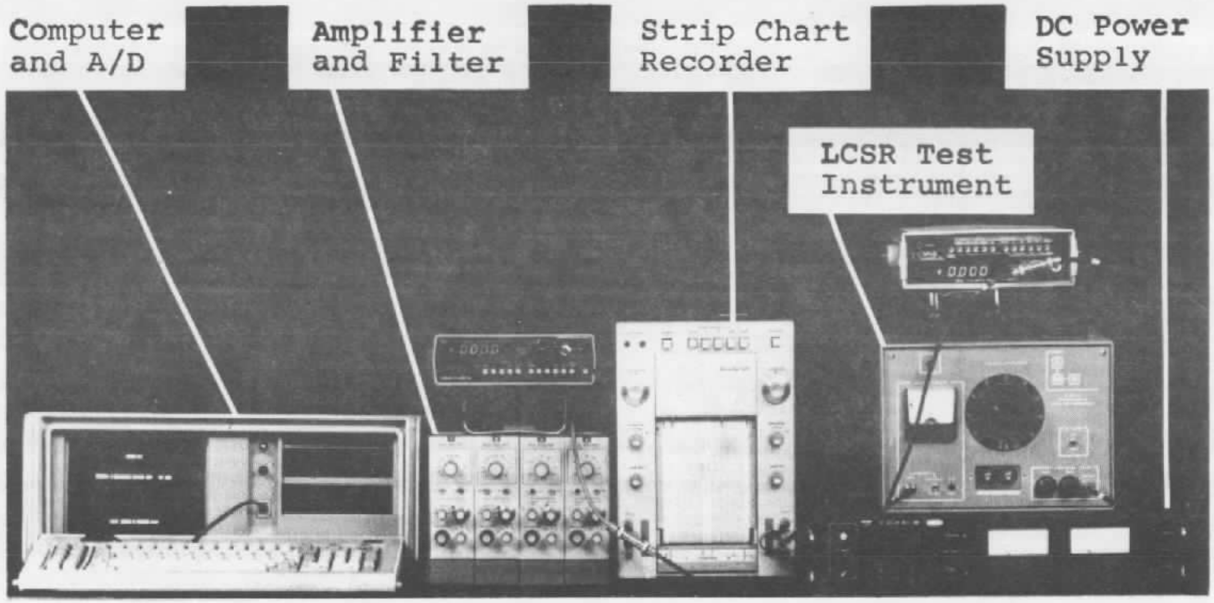
2. Turn on the heating current. The magnitude, type (AC or DC) and duration of the current were varied in the program.

3. Turn off the heating current and record the thermocouple emf on the strip chart recorder and the digital data acquisition system as the thermocouple



Rotating Tank and Associated Hardware

Figure 5.1



Data Acquisition System

Figure 5.2

Table 5.1

Components of Data Acquisition System

Item	Description	Model No.
1	LCSR Test Instrument	AMS ETC-1
2	DC Power Supply	Sorensen DCR 80-6B
3	Stripchart Recorder	Gould Recorder 220
4	Amplifier/Filter	Gould Model 134615-20
5	Digital Multimeters	Valhalla Model 4440
6	Microcomputers	IBM Portable PC
7	A/D Converter	Data Translation 2801-A

Above equipment had valid NBS traceable calibrations as applicable while they were in-use in this project.

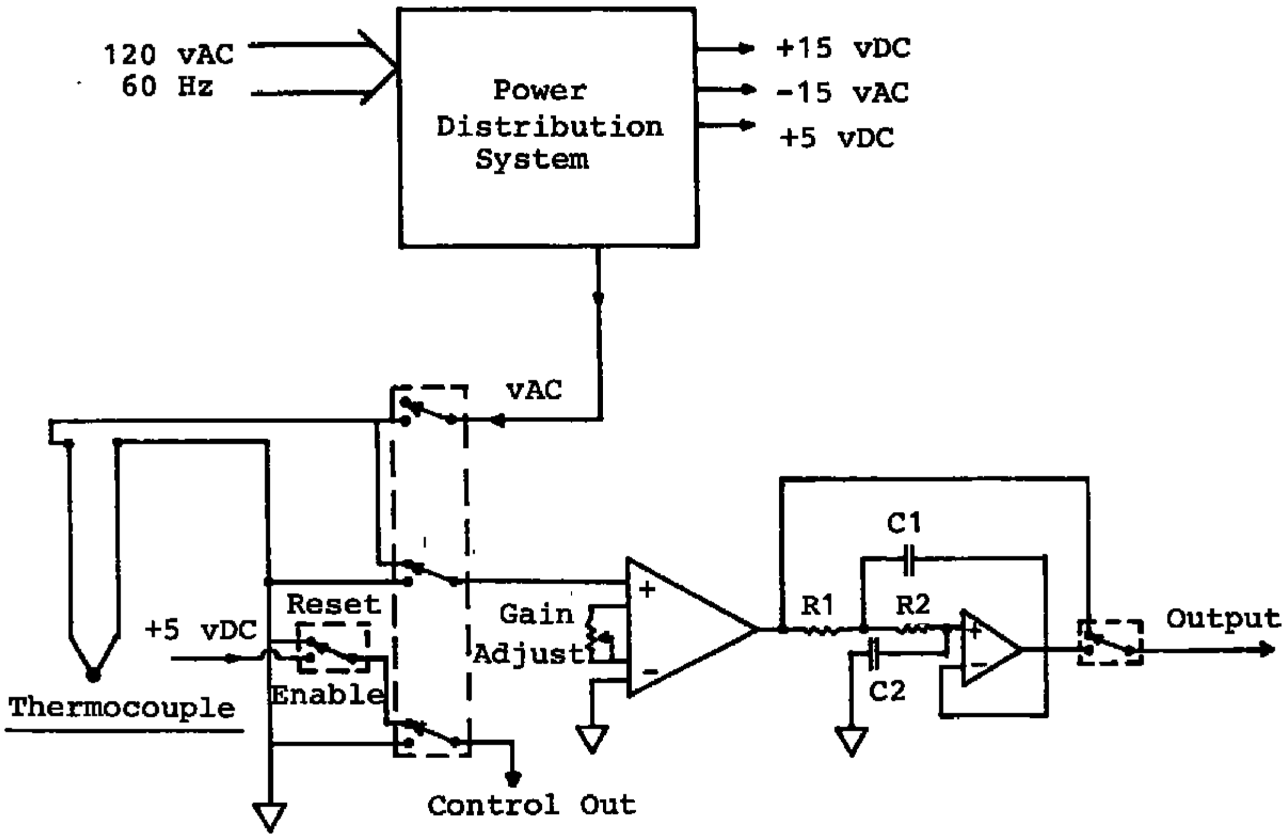


Figure 5.3: Simplified Schematic of ETC-1.

cools.

The LCSR data were sampled with a digital data acquisition system involving an IBM microcomputer and a Data Translation analog-to-digital (A/D) converter. The sampling was initiated by a trigger signal from the ETC-1 that occurs when the current to the thermocouple is turned off. The data were sampled until the LCSR signal reached steady state. The sampling rate and total number of points sampled were selected based on the response behavior of the thermocouple under test. Sampling rates ranged from about 5 to 50 milliseconds for various thermocouples and various test conditions in this project. The number of data points sampled ranged from 1000 to 3000. The data were stored on floppy disks and subsequently analyzed. The analysis involved both graphical exponential peeling and a least squares fitting of the data to identify the thermocouple time constants.

For validation testing, the thermocouple's time constant was also measured directly at the same water flow condition as existed in LCSR testing. The method for direct measurement involved plunge testing. The procedure was:

1. Connect the sensor on the pneumatically-driven cylinder above the flowing water.

2. Apply a flow of heated air around the sensor and wait for the sensor output signal to stabilize.

3. Actuate the drive mechanism in order to plunge the

sensor rapidly into the flowing water.

4. Record the transient on the strip chart recorder.

The sensor's time constant was determined by evaluating the time for the response to cover 63.2 per cent of the total span. A stripchart recorder tracing of a typical data with calculation of time constant is shown in Figure 5.4.

The water test facility was also used to study the effect of fluid flow rate on thermocouple response time. Two different thermocouples were used in this study. Each thermocouple was plunge tested in water at four different flow rates. The sensor time constant was measured at each flow rate and the data were used to identify the response versus flow correlation for the thermocouple tested. The results are discussed in Section 6. The correlations were then used to obtain time response estimates in flowing air. These estimates were compared with actual time constant measurements in air to determine the accuracy of the correlations.

5.2. Testing in Air

An air loop was built as shown in Figure 5.5. Testing involved the same procedure as was used for testing in water. The air flow rate was adjusted to approximately 6 meters/sec. The flow was measured with a pitot tube.

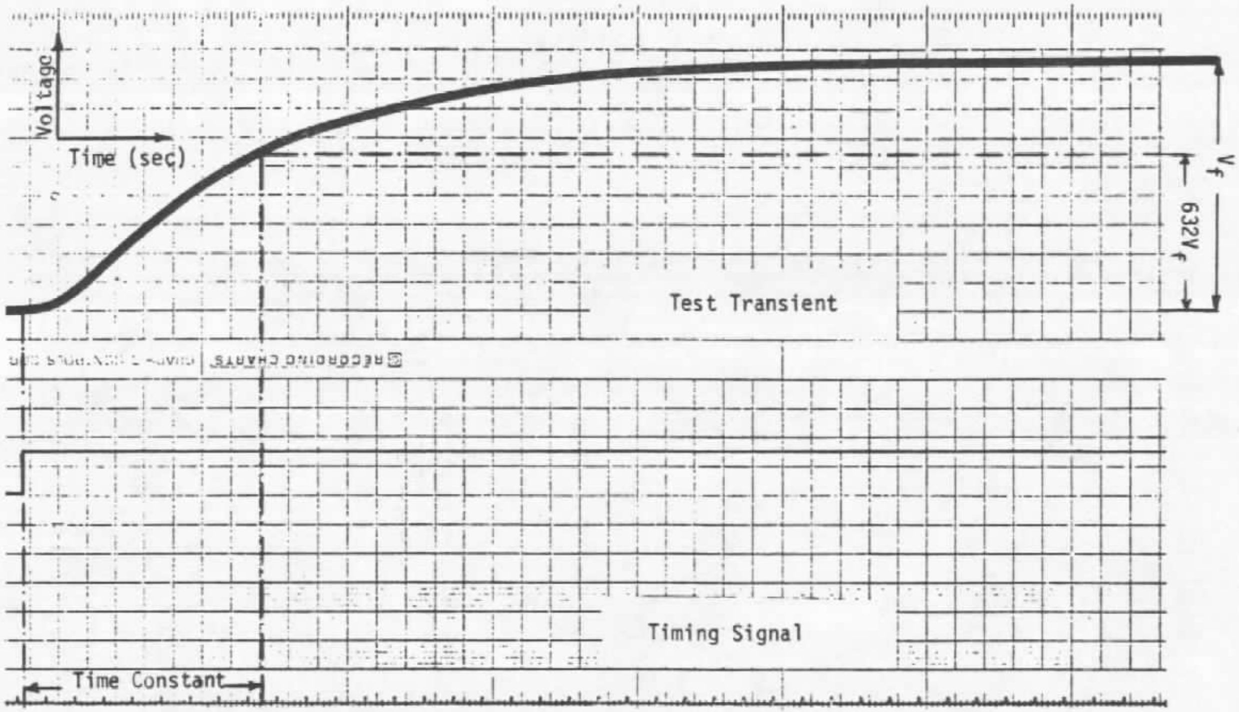
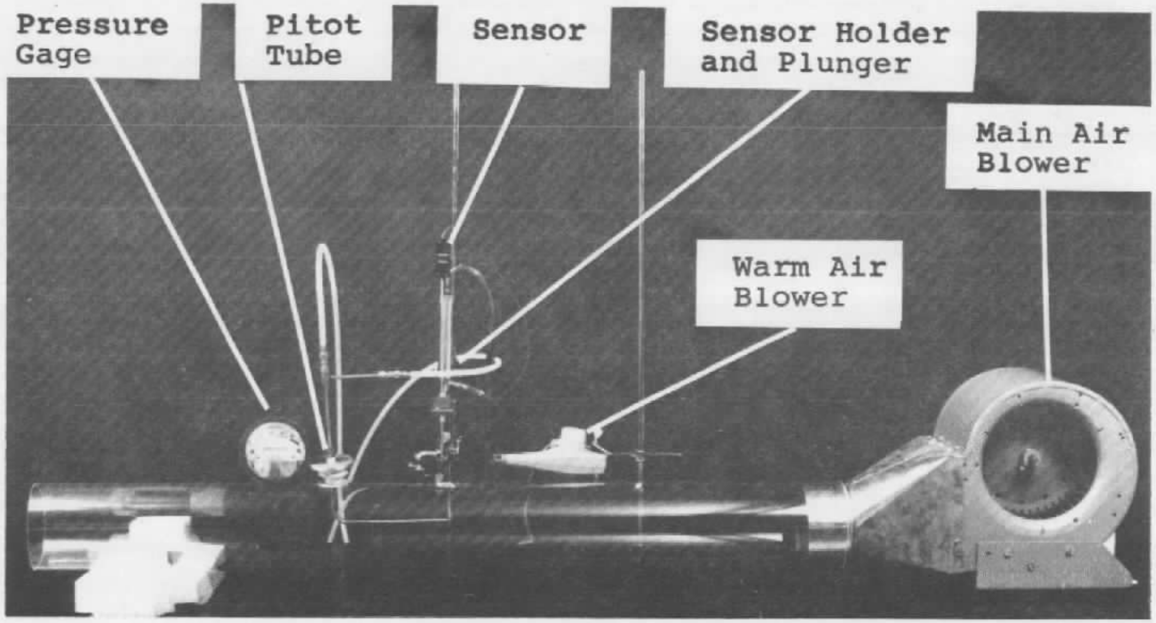


Figure 5.4: A Typical Plunge Test Transient with Illustration of Time Constant.



Air Loop and Associated Hardware

Figure 5.5

The air loop was built for three reasons:

1. To examine the LCSR testability of the exposed junction thermocouples. These cannot be LCSR tested in water. The water conductivity shorts the thermocouple wires and gives useless LCSR signals.

2. To accumulate experience with LCSR testing in flowing air which is the medium of main interest in turbine engine test facilities.

3. To examine the validity of time constant versus flow correlations that can be generated by testing in water and used to estimate the response time in any other medium.

The same signal conditioning and signal recording equipment were used for testing in water and in air.

6. RESULTS

Test results were obtained to provide information on the main uncertainties in test equipment design, test procedures, and validity of the LCSR method on thermocouples of interest. This work is described in this chapter for each of the main project activities. All data and figures in this chapter are from laboratory experiments performed for this project.

6.1. Baseline Time Constant Measurements

The thermocouples selected for this study were first tested by the plunge method and their baseline time constants were identified. These were tested in water and/or air. A variety of thermocouples was tested including some commonly used commercial probes and some made of general purpose thermocouple wires. The latter were made in accordance with information obtained for AEDC about typical thermocouples in turbine engine test facilities. The junctions of these thermocouples were butt welded, lap welded, lap and silver soldered, or twisted and silver soldered as specified by AEDC. These are shown in Appendix A along with a listing of the thermocouples acquired for this project. The list includes type T thermocouples which were added when information obtained for AEDC indicated that type T thermocouples were of interest in turbine engine test facilities. The information also revealed that type E thermocouples are rarely used at AEDC. Therefore, more attention was given to testing of type T instead of type E thermocouples.

Typical time constant results for sheathed thermocouples are compared in Table 6.1 for the tests in room temperature water and room temperature air. Note that the thermocouples responded much faster in water than in air even though the air was flowing at a higher rate.

Typical time constant results for exposed junction (bare) thermocouples are given in Table 6.2. The response times are about 2 seconds compared with about 15 seconds for the sheathed thermocouples. Typical plunge test transients are shown in Figures 6.1 and 6.2 for a sheathed thermocouple in water and in air.

An I.D. number was assigned to each thermocouple to facilitate tabulating the results. The I.D. corresponds to thermocouple specifications as given in Appendix A.

6.2. Baseline LCSR Tests

The accuracy of the LCSR results depends on the quality of the test data as determined by signal-to-noise ratio. There are two ways to enhance the signal-to-noise ratio in the LCSR test. One is to use a high current to cause a larger heating in the

Table 6.1

Time Constants of Sheathed Thermocouples

Item	Thermocouple Type	Thermocouple I.D.	Time Constant (Sec.) In Water	Time Constant (Sec.) In Air
1	J	J-T	1.3	14.8
2	K	K-T	1.3	15.0
3	E	E-Q	2.0	15.3

The test results in water are from plunge in approximately 1 m/sec. and the test results in air are from plunge in approximately 16 m/sec.

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

Table 6.2

Time Constants of Exposed Junction Thermocouples in Air

Item	Thermocouple Type	Thermocouple I.D.	Time Constant (Sec.)
1	J	J-TSS	2.0
2	J	J-LW	1.5
3	J	J-LSS	2.1
4	J	J-BW	1.3
5	K	K-TSS	2.2
6	K	K-LW	2.0
7	K	K-LSS	2.8
8	K	K-BW	1.4
9	T	T-TSS	3.5
10	T	T-LW	2.5
11	T	T-LSS	1.8
12	T	T-BW	2.0

Above results are from tests in room temperature air at approximately 6 m/sec.

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

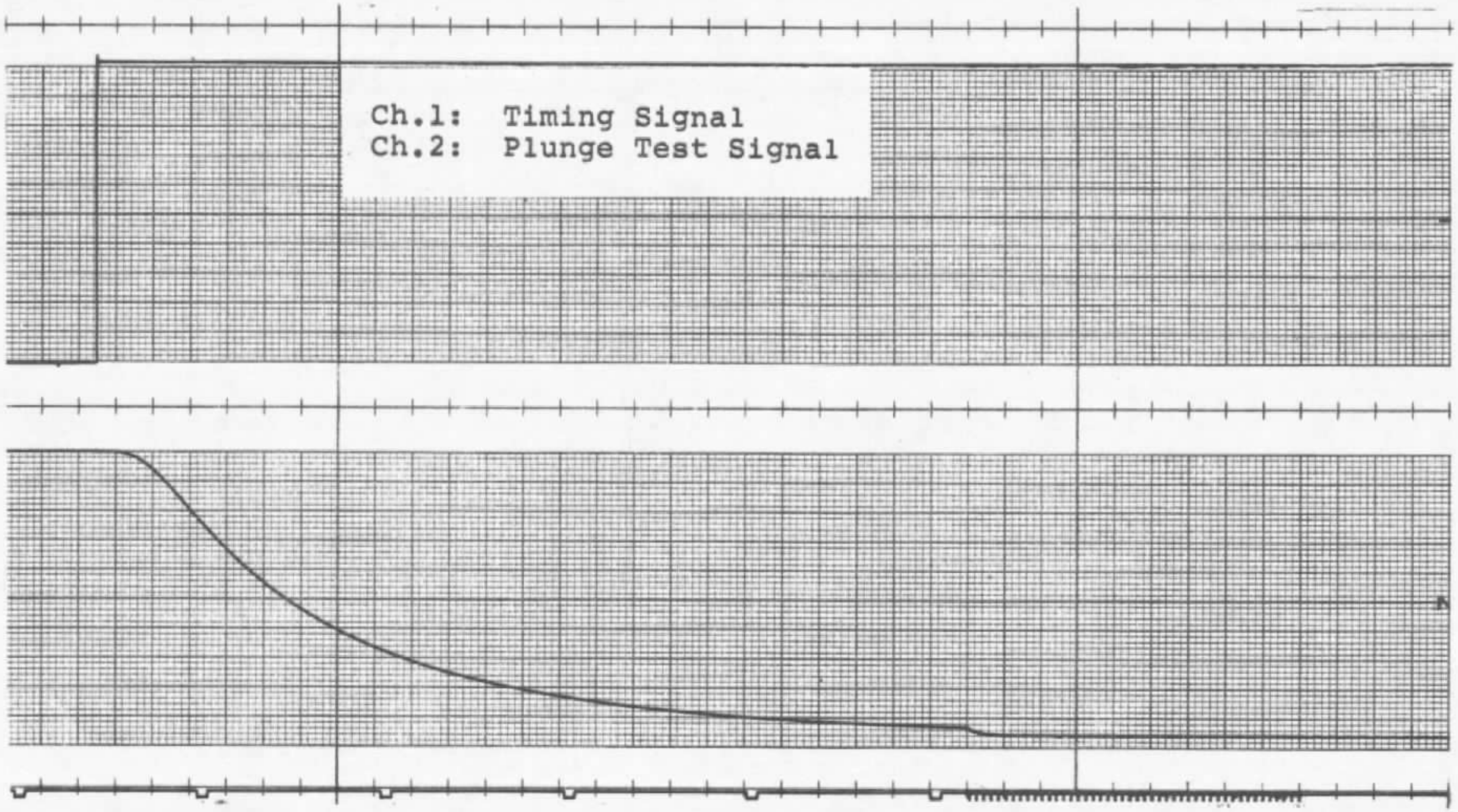


Figure 6.1: A Plunge Test Output for a Sheathed Thermocouple Tested in Room Temperature Water at 1 m/sec Flow. Type K (ID K-T). Chart Speed = 25 mm/sec.

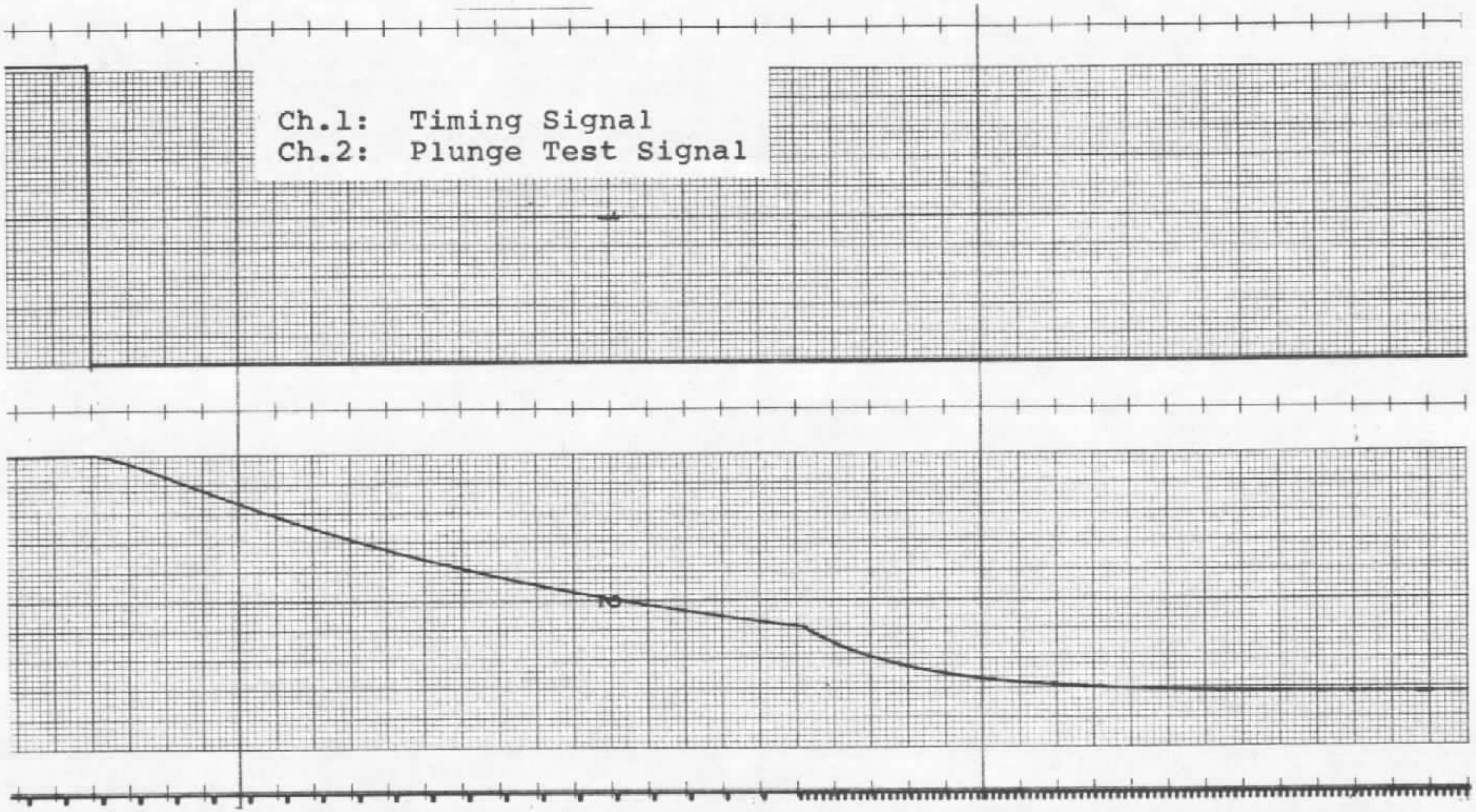


Figure 6.2: A Plunge Test Output for a Sheathed Thermocouple Tested in Room Temperature Air at 6 m/sec Flow. Type K (ID K-T). Chart Speed = 5 mm/sec.

thermocouple junction, and the other is to improve the data quality by analog signal conditioning and digital filtering. One of the objectives of this project was to avoid lethal test currents. Therefore, attempts were made to enhance the data quality by analog and digital signal conditioning rather than using a higher current. Figure 6.3 shows an enhanced LCSR transient. This data set has undergone proper signal conditioning and filtering before it was plotted. This and all other LCSR transients given in this report are inverted and normalized before plotting.

A typical LCSR data set without extensive signal conditioning is shown in Figure 6.4. Note that the data has high and low frequency oscillations (noise) and drift. The noise can be removed by filtering and averaging multiple data sets but the drift cannot be eliminated readily. The drift was encountered, in varying quantities, in almost all LCSR data sets obtained in this project with both AC and DC heating. The amount of the drift depended on the current level, heating time, and on the speed of thermocouple response. Some thermocouples showed less drift than the others. The drift causes error in the LCSR results unless it is properly removed in the analysis as was done in all data analysis in this project. Fortunately, the drift-contaminated data usually have two distinct regions, a region with drift and another without the drift. It was found that good results can be obtained when the drift-contaminated

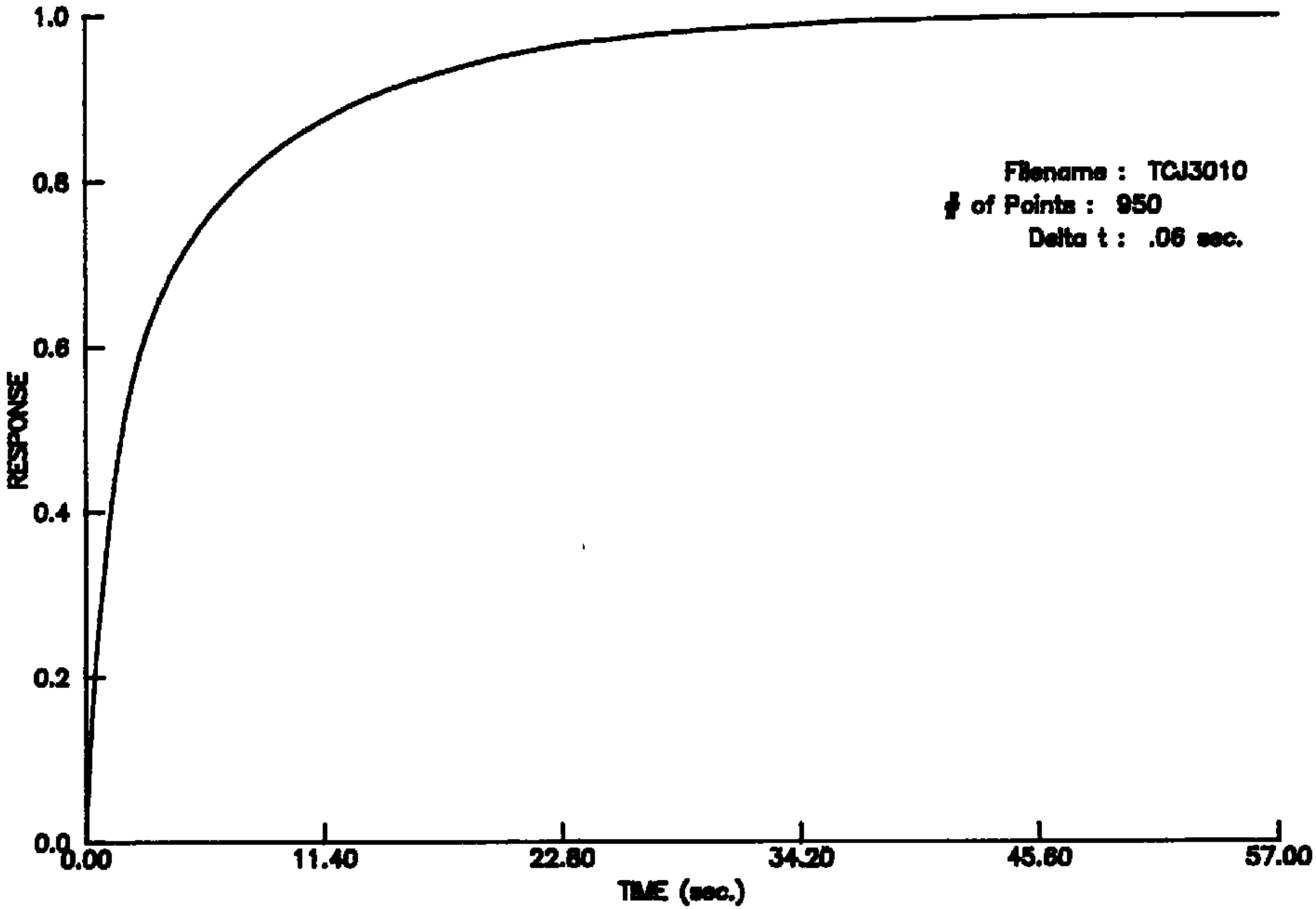


Figure 6.3: An Enhanced LCSR Transient.

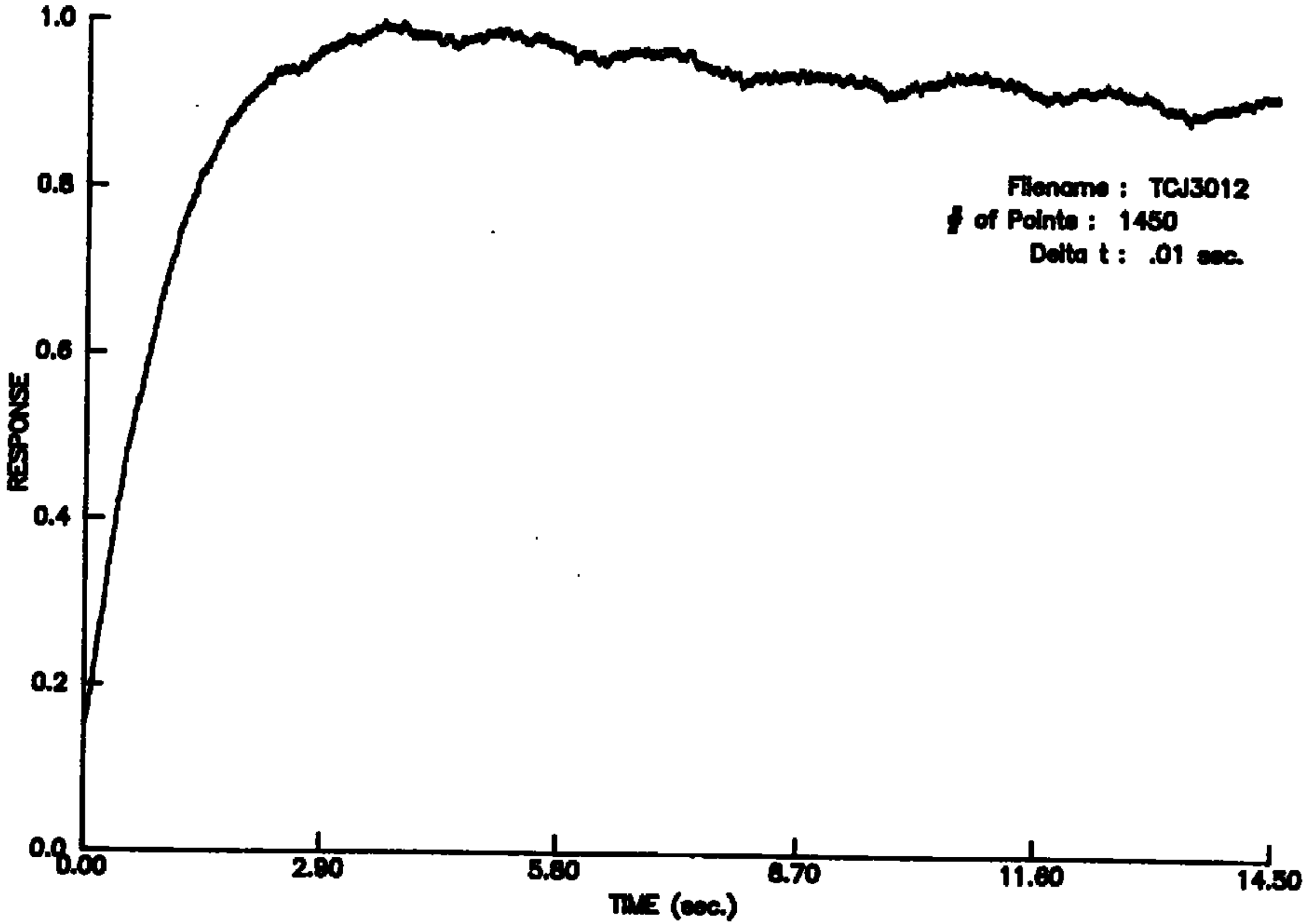


Figure 6.4: A Typical Raw LCSR Transient.

region is removed from the data before analysis.

The drift is believed to be, at least partly, due to heating of the reference junction during a LCSR test. However, the drift could not be eliminated from the analog data even though tests were performed with reference junction removed during the heating cycle and very large copper blocks used as reference junction. These usually helped reduce the drift but did not eliminate it.

The improvement in signal quality as evident by a comparison of Figures 6.3 and 6.4, is one of the accomplishments of this project. A good signal conditioning practice reduces the need for hazardous high currents while providing suitable data for reliable analysis.

6.3. AC versus DC Heating

The LCSR test equipment was used for thermocouple testing with two different power supplies (an 80 volt, 6 amp, variable DC supply and a 60 Hz, 0.300 KVA AC supply in the ETC-1 test instrument). Typical LCSR transients are compared in Figure 6.5. There are no qualitative differences in these tests. During DC tests, the polarity was changed and the tests were repeated to determine any Peltier heating or cooling effect in the junction. The test data did not show a significant polarity effect.

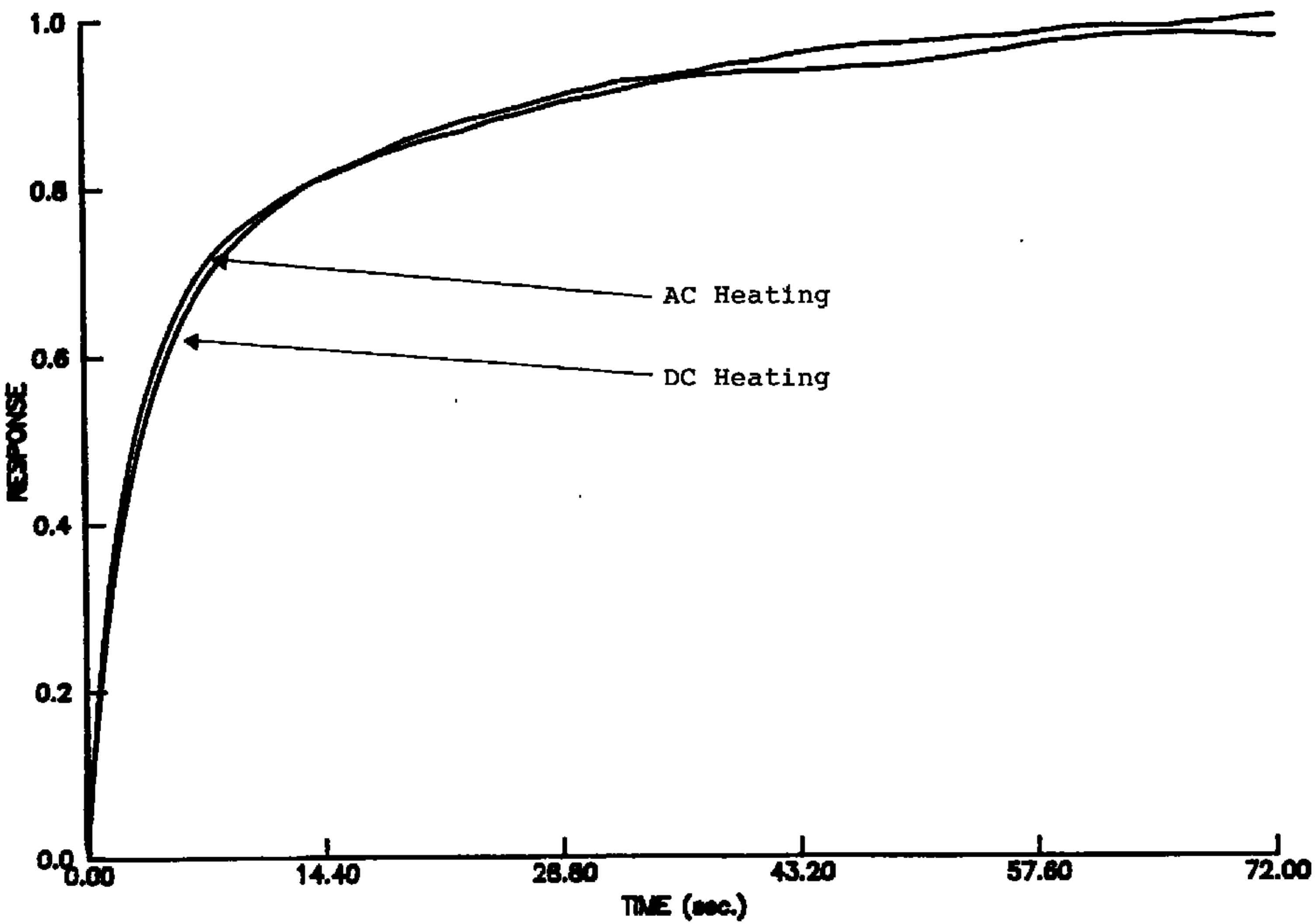


Figure 6.5: A Typical LCSR Transient with AC and DC Heating.

A good basis for comparison of the two heating methods is the agreement of time constant estimates obtained from the data analysis. (The validity of these estimates is discussed in Section 6.5.) These are summarized in Table 6.3 for the tests performed to evaluate the heating method. Table 6.3 shows that DC and AC perform equally well for the sensors tested. Therefore, the designer of the LCSR test equipment can choose either one of the two heating methods.

During the evaluation of heating methods, investigations were also made on the effect of the duration of the heating and the magnitude of the heating current. Large heating currents and larger heating times were found to provide larger LCSR signals but also gave larger drift in the data which is undesirable. It was found that good LCSR data can not be obtained with currents of less than 1 amp and the best combination of heating current and heating time depends on the sensor and the test environment. For example, for the sheathed thermocouples tested in water, the best combination was found to be 5 seconds heating with 3 amps.

The LCSR results for two type J thermocouples are given in Table 6.4 as a function of heating time. The changes in the results are believed to be mostly due to uncertainty in the test and its repeatability rather than any effect of heating period on response time.

Table 6.3

Comparison of LCSR Results from AC and DC Heating

Item	Thermocouple Type	Thermocouple I.D.	Time Constant (sec.) AC	Time Constant (sec.) DC
1	T	T-LSS	2.1	2.3
2	T	T-TSS	4.0	3.8
3	J	J-T	1.4	1.5
4	K	K-T	1.4	1.5

Items 1 and 2 were tested in air at approximately 6 m/sec.

Items 3 and 4 were tested in water at approximately 1 m/sec.

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

Table 6.4

Effect of Heating Time on LCSR Results

Thermocouple Type	Thermocouple I.D.	Heating Time (sec.)	Time Constant (sec.)
J	J-Q	3	1.5
		5	1.5
		10	1.1
		15	1.2
		20	1.1
J	J-T	30	17.4
		45	18.0
		60	18.2

Above results are from tests with a heating current of 3 amps. The J-Q thermocouple was tested in water at 1 m/sec. and the J-T thermocouple in air at 16 m/sec.

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

6.4. LCSR Data for Various Thermocouples

Since almost all prior experience on LCSR testing of thermocouples involved type K sensors, it was necessary to investigate the general characteristics of LCSR signals obtained for other sensor types. Figures 6.6 through 6.9 show typical raw data for type J, K, E and T thermocouples. Since the responses are expected to be defined by sums of exponential modes, semi-logarithmic plotting should show nearly linear behavior (especially far into the transient after faster modes have died away). Figures 6.10 through 6.13 show typical semi-logarithmic plots for thermocouples with one or more apparent modal time constants. These show that all thermocouple types tested provide data of comparable quality.

6.5. Validity of LCSR Results

Before the LCSR method is used for in-situ testing of thermocouples installed in operating processes, it is essential to obtain laboratory validation of the method and the results. This is accomplished by performing LCSR and plunge tests in the same test fluid at the same flow and temperature in the laboratory. This is conveniently done in flowing water or air using the following procedure:

1. Establish fluid flow (water or air).
2. Bring the sensor to thermal equilibrium outside the

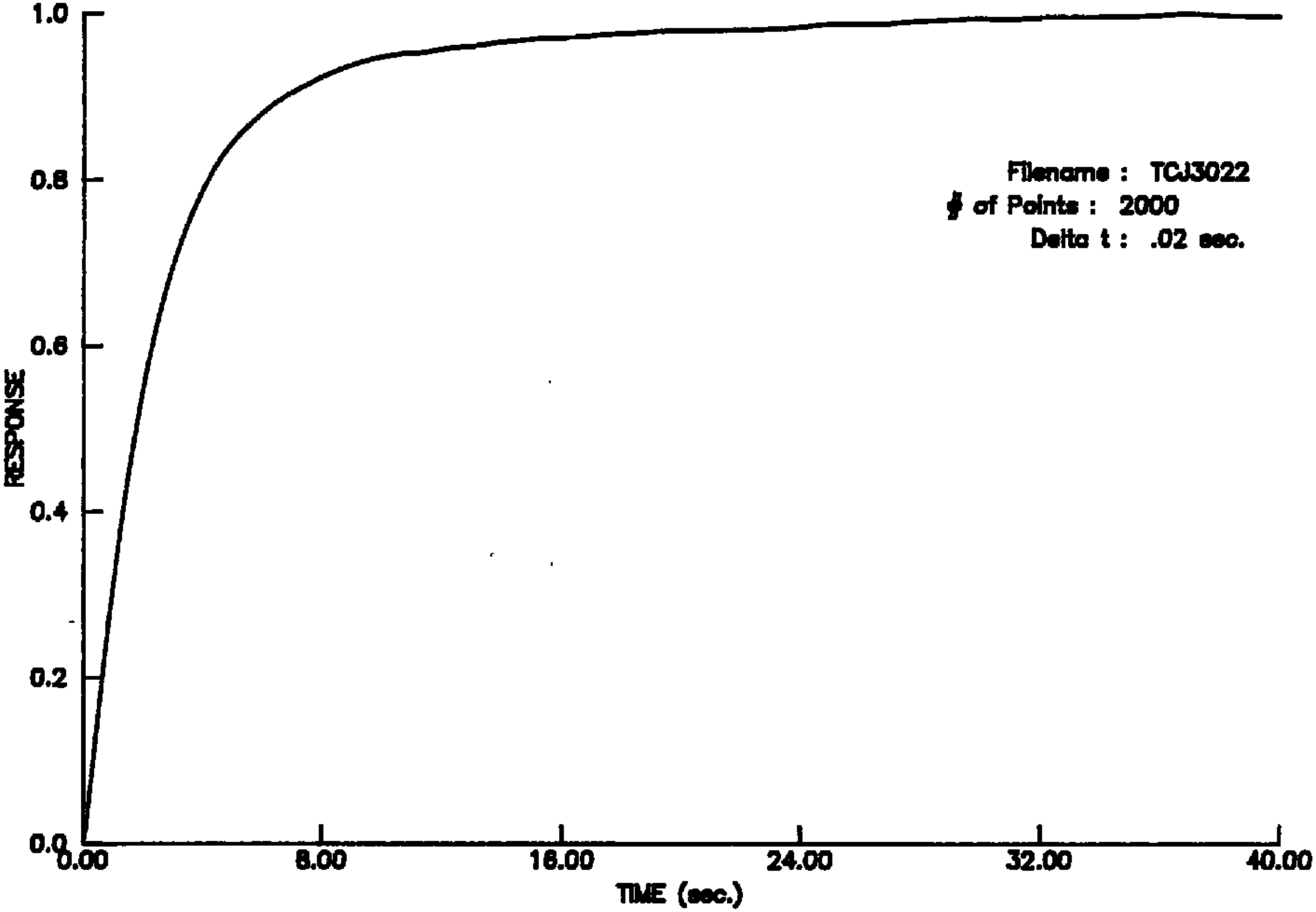


Figure 6.6: A LCSR Transient for a Type J Thermocouple.

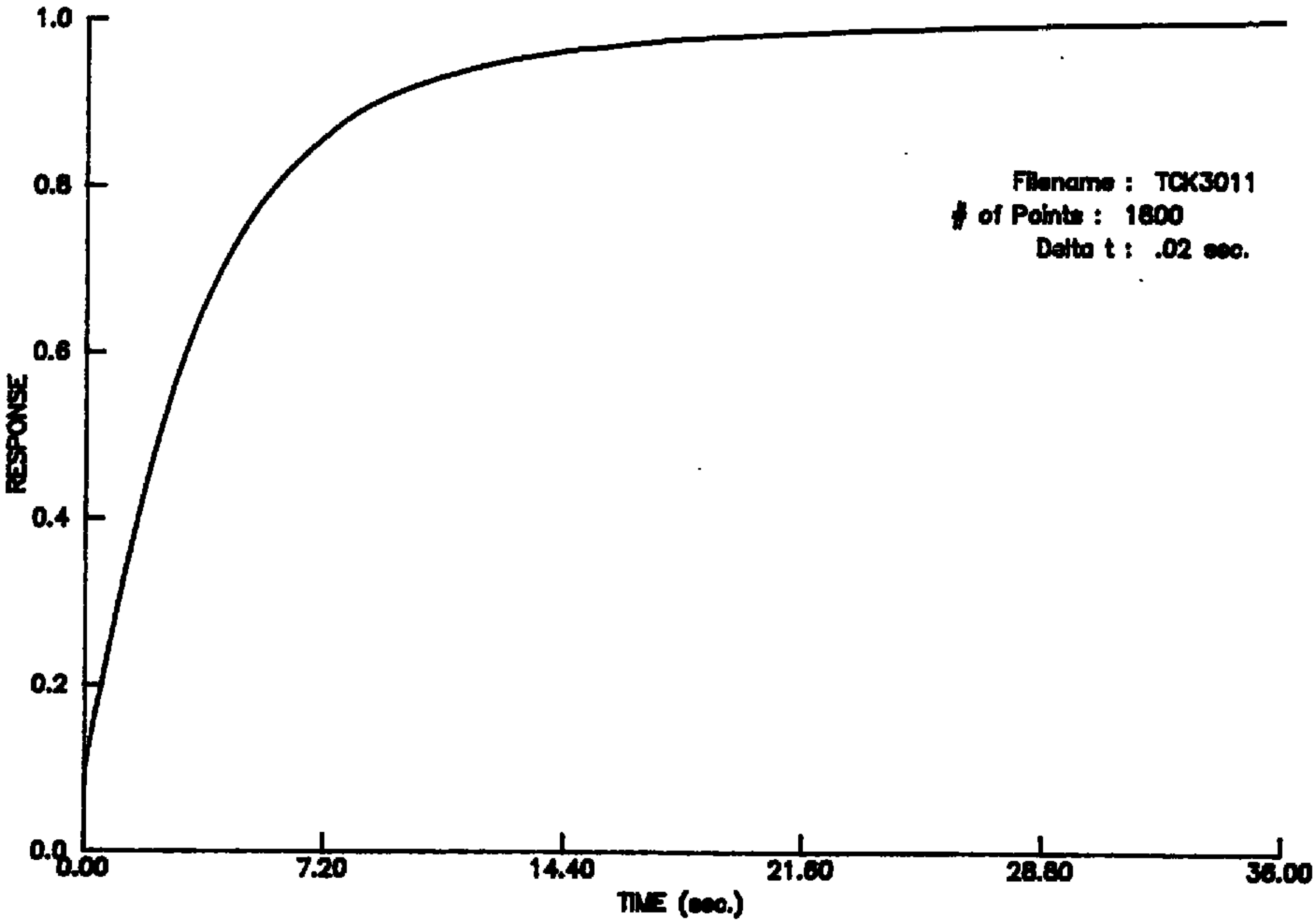


Figure 6.7: A LCSR Transient for a Type K Thermocouple.

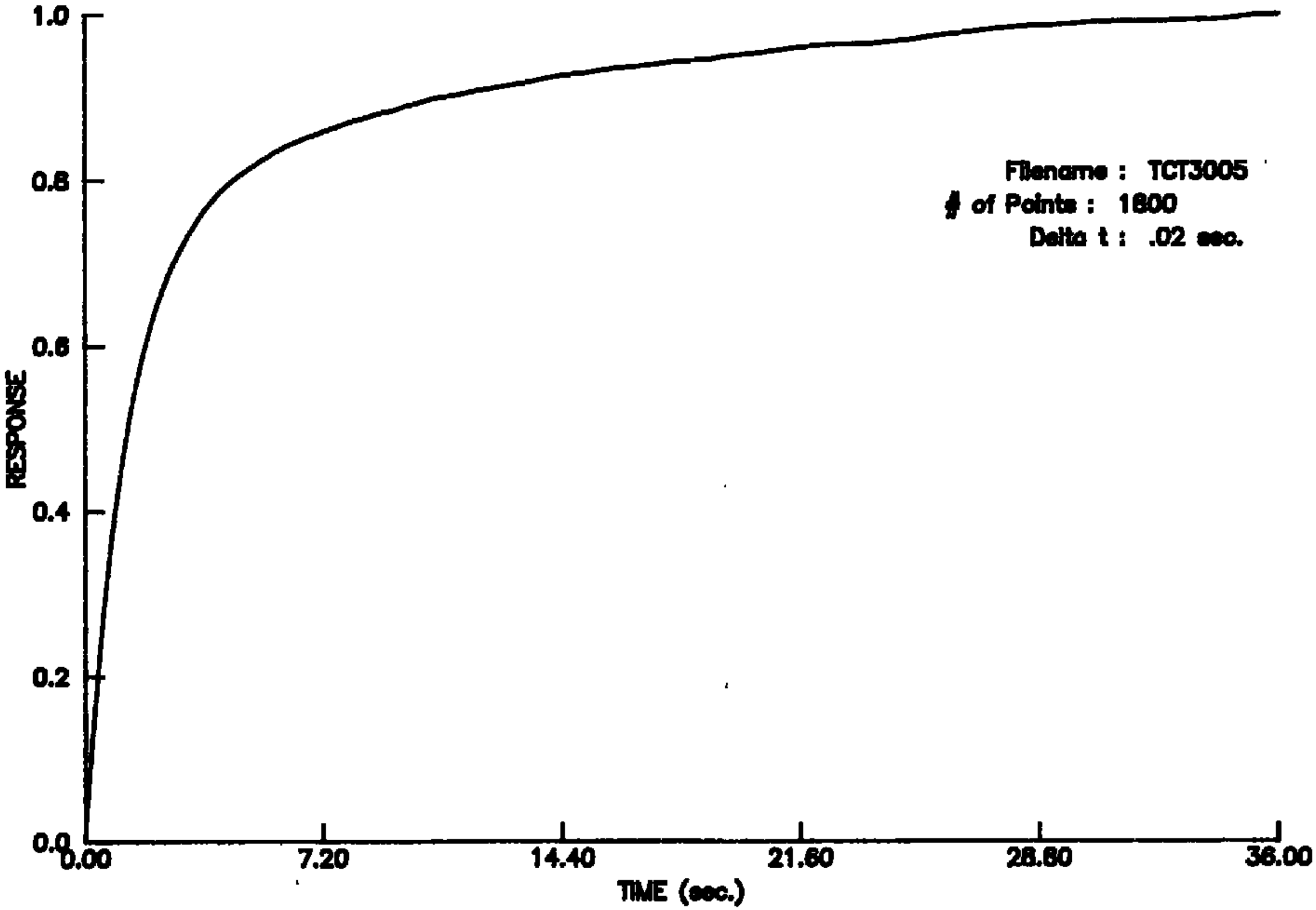


Figure 6.8: A LCSR Transient for a Type T Thermocouple.

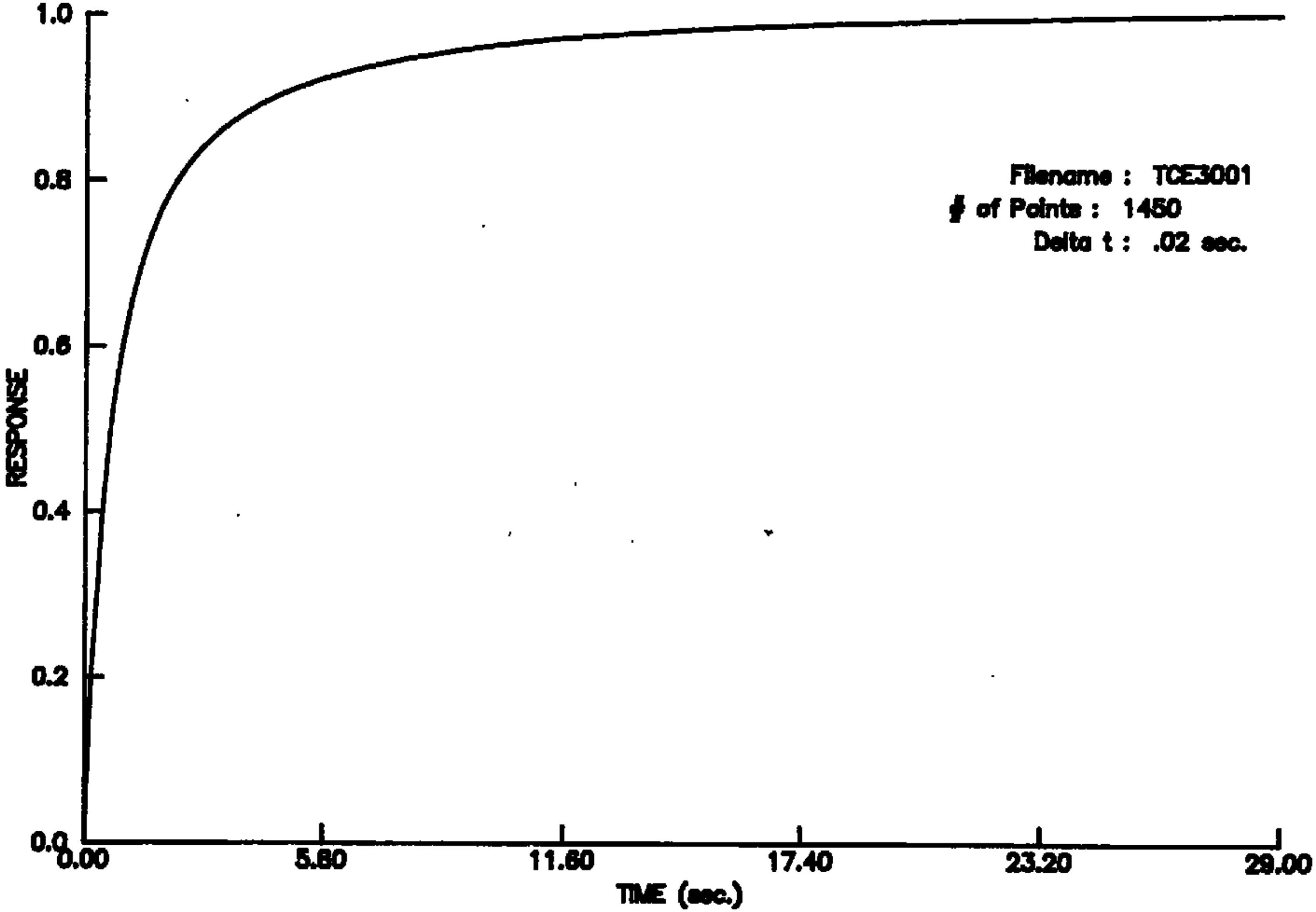


Figure 6.9: A LCSR Transient for a Type E Thermocouple.

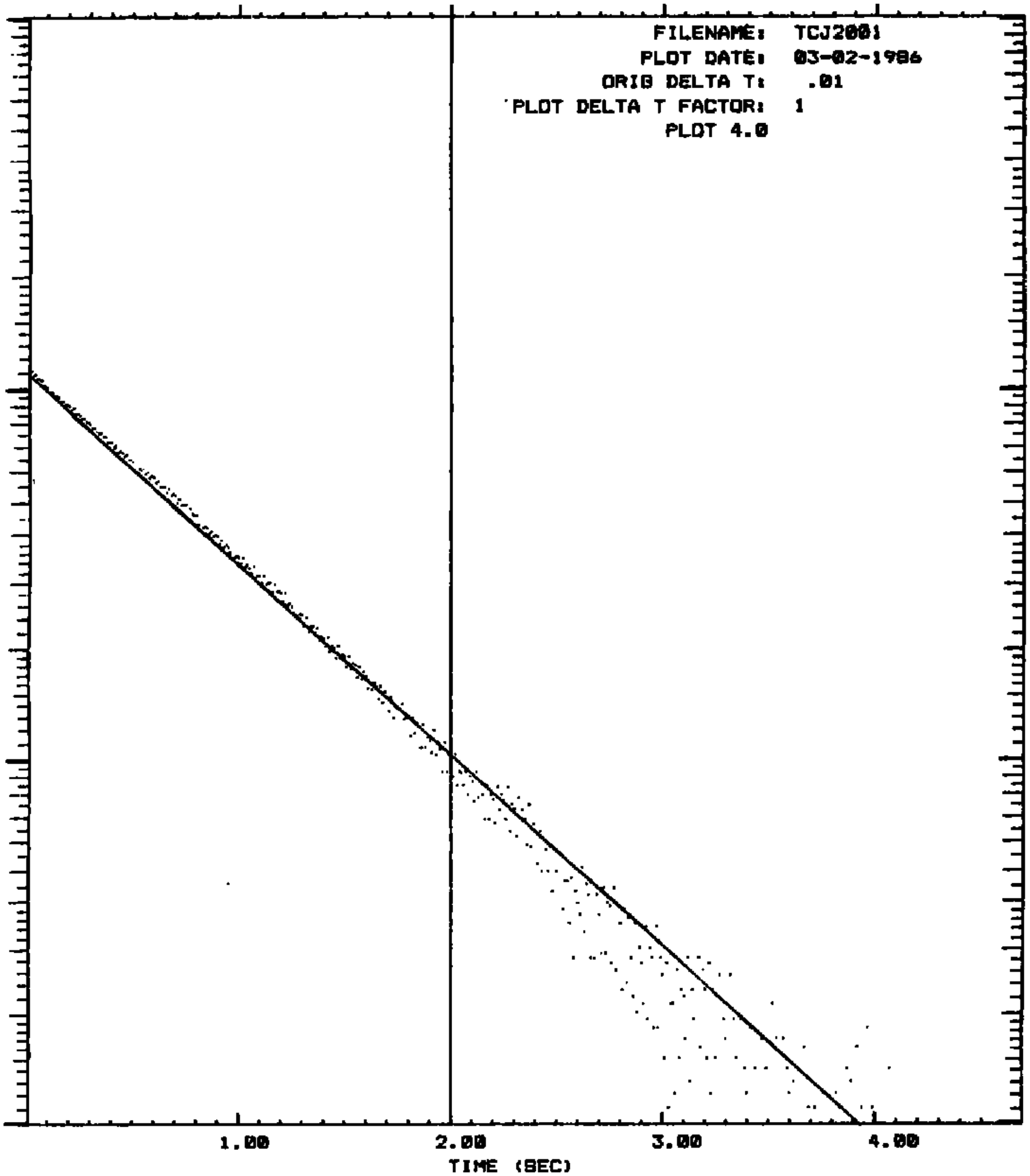


Figure 6.10: A Semi-Logarithmic Plot of LCSR Data for a Type J Thermocouple.

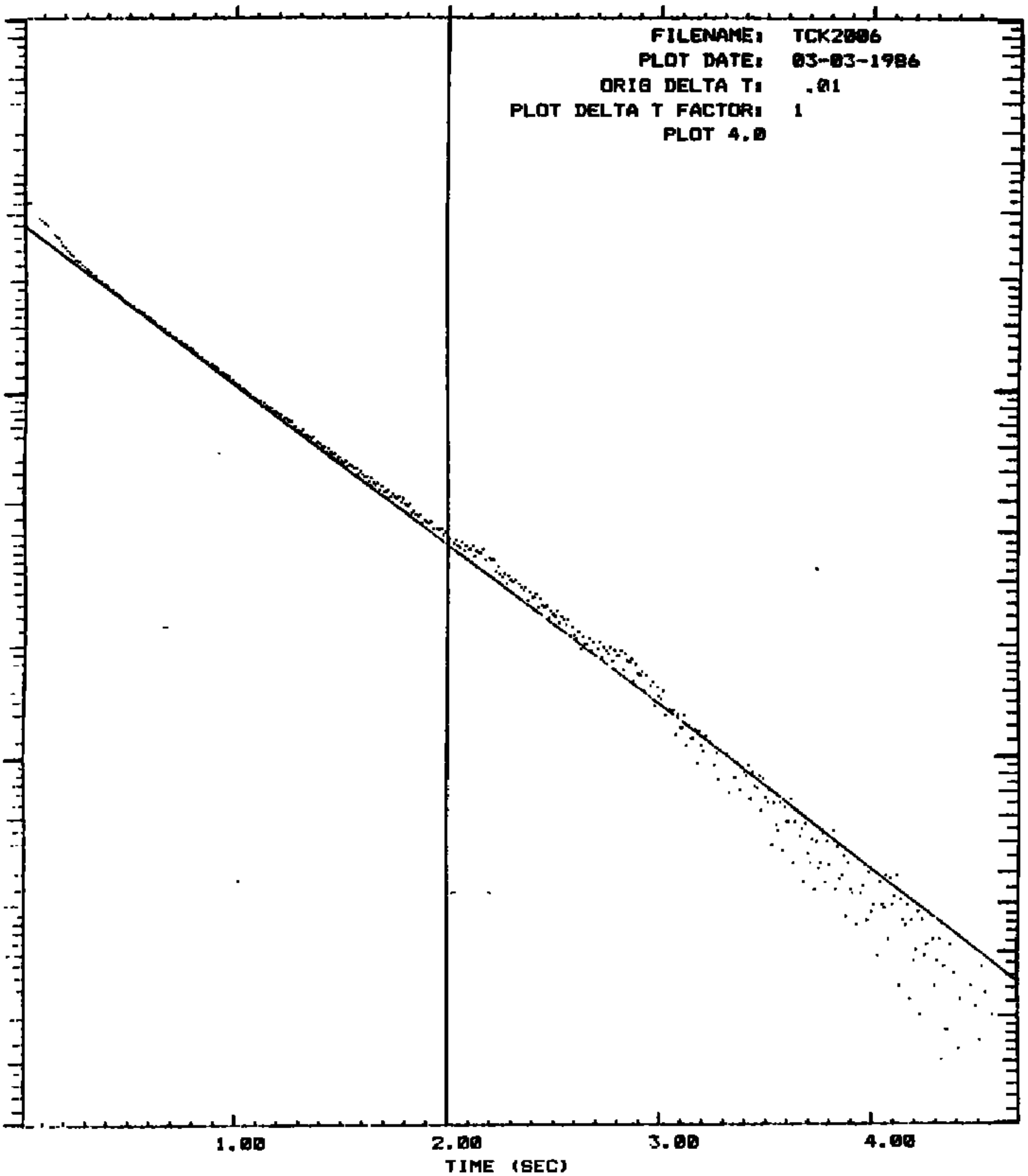


Figure 6.11: A Semi-Logarithmic Plot of LCSR Data for a Type K Thermocouple.

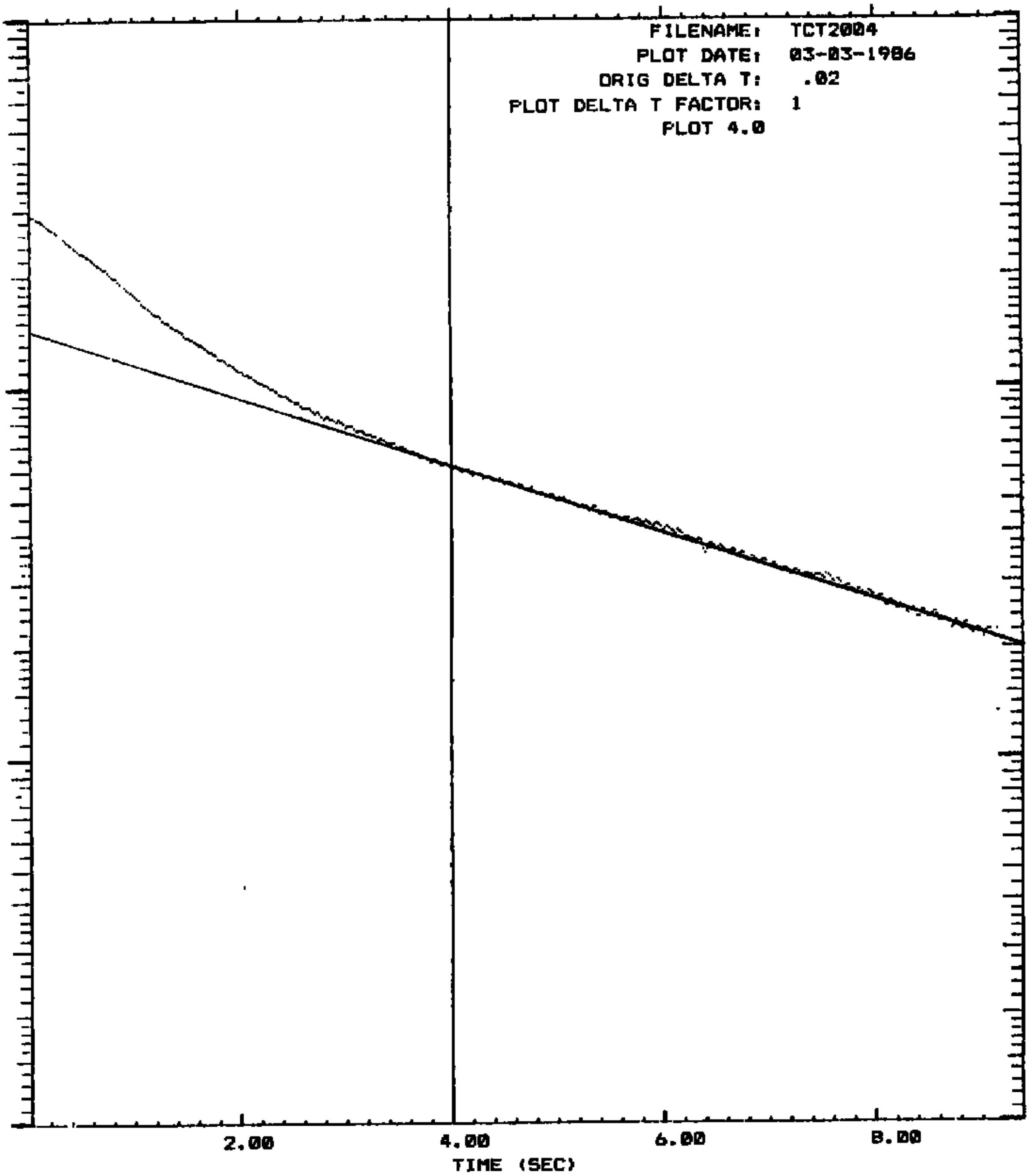


Figure 6.12: A Semi-Logarithmic Plot of LCSR Data for a Type T Thermocouple.

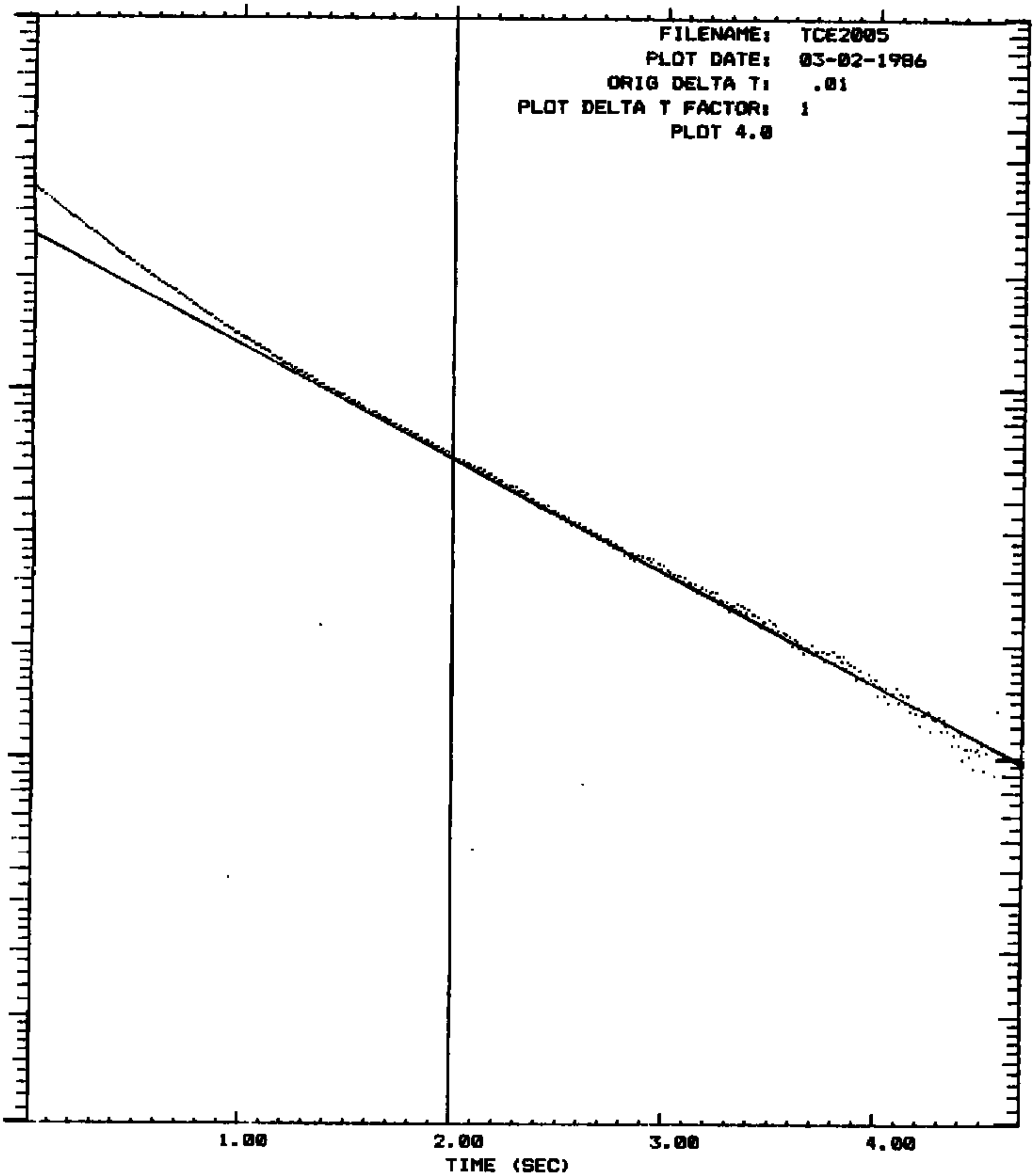


Figure 6.13: A Semi-Logarithmic Plot of LCSR Data for a Type E Thermocouple.

test fluid with a heated air stream.

3. Plunge the sensor rapidly into the flowing fluid and record the transient.

4. Evaluate the time constant by measuring the time required to span 63.2% of the total response.

5. While the sensor is inserted in the flowing fluid, perform a LCSR test and record the data digitally.

6. Analyze the LCSR data to obtain a time constant estimate.

7. Compare the results from steps 4 and 6.

The results of this test program are shown in Table 6.5. These show good agreement between the results of the two tests on each sensor. The good agreement indicates the validity of the LCSR test and the data analysis. The average of the differences between the results of the two tests on each sensor is about 20 percent. That is, the LCSR test can be used to measure the response time of a thermocouple to within about 20 percent of the actual value. The advantage of this test is that it can be performed in-situ and it accounts for all environmental and installation factors that can affect the response time of an installed sensor.

6.6. Time Response and Frequency Response

In the past, the results of LCSR testing have most often been predicted as a single numerical quantity, the time constant. However, the LCSR method permits constructing estimates of the

Table 6.5

LCSR Validation Results

Item	Thermocouple Type	Thermocouple I.D.	Test Condition	Time Constant (sec.) Plunge	Time Constant (sec.) LCSR
1	E	E-T	Water, 1 m/sec.	3.1	3.5
2	E	E-Q	Water, 1 m/sec.	2.0	2.1
3	J	J-T	Water, 1 m/sec.	1.3	1.4
4	K	K-T	Water, 1 m/sec.	1.3	1.4
5	J	J-Q	Water, 1 m/sec.	2.1	1.5
6	E	E-Q	Air, 16 m/sec.	15.3	18.6
7	J	J-T	Air, 16 m/sec.	14.8	17.4
8	K	K-T	Air, 16 m/sec.	15.0	17.2
9	J	J-LW	Air, 6 m/sec.	1.5	1.7
10	J	J-BW	Air, 6 m/sec.	1.3	1.7
11	J	J-LSS	Air, 6 m/sec.	2.1	2.8
12	J	J-TSS	Air, 6 m/sec.	2.0	2.3
13	K	K-LW	Air, 6 m/sec.	2.0	2.7
14	K	K-BW	Air, 6 m/sec.	1.4	1.8
15	K	K-LSS	Air, 6 m/sec.	2.8	3.0
16	K	K-TSS	Air, 6 m/sec.	2.2	3.0
17	T	T-LW	Air, 6 m/sec.	2.5	2.5
18	T	T-BW	Air, 6 m/sec.	2.0	2.6
19	T	T-LSS	Air, 6 m/sec.	1.8	2.1
20	T	T-TSS	Air, 6 m/sec.	3.5	4.1

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

complete time response for any temperature perturbation or the frequency response. Figures 6.14 and 6.15 show typical estimates of step response and frequency response obtained from analysis of LCSR data for a thermocouple.

The step response curve is shown on the same plot with the corresponding LCSR raw data transient and the actual step response from a plunge test. This shows that the analysis of LCSR test gives the same step response that would be obtained if the sensor experiences a step change in surrounding temperature.

6.7. Connector Effects

If connectors are used in the thermoelectric circuits, they may have an effect on LCSR tests if they are not made of the same material as the thermocouple wires. As shown in Section 3, these connectors would not affect routine temperature measurements if they did not experience a temperature gradient across the connector. However, in LCSR testing, temperature gradients at connectors are likely because of the discontinuities in electrical resistance at the connectors.

The influence of connectors was investigated experimentally by inserting various male/female quick disconnect connectors in thermocouple circuits during LCSR testing. This increased the drift in the data as shown in Figure 6.16. The difference between the two transients in Figure 6.16 indicates that, due to

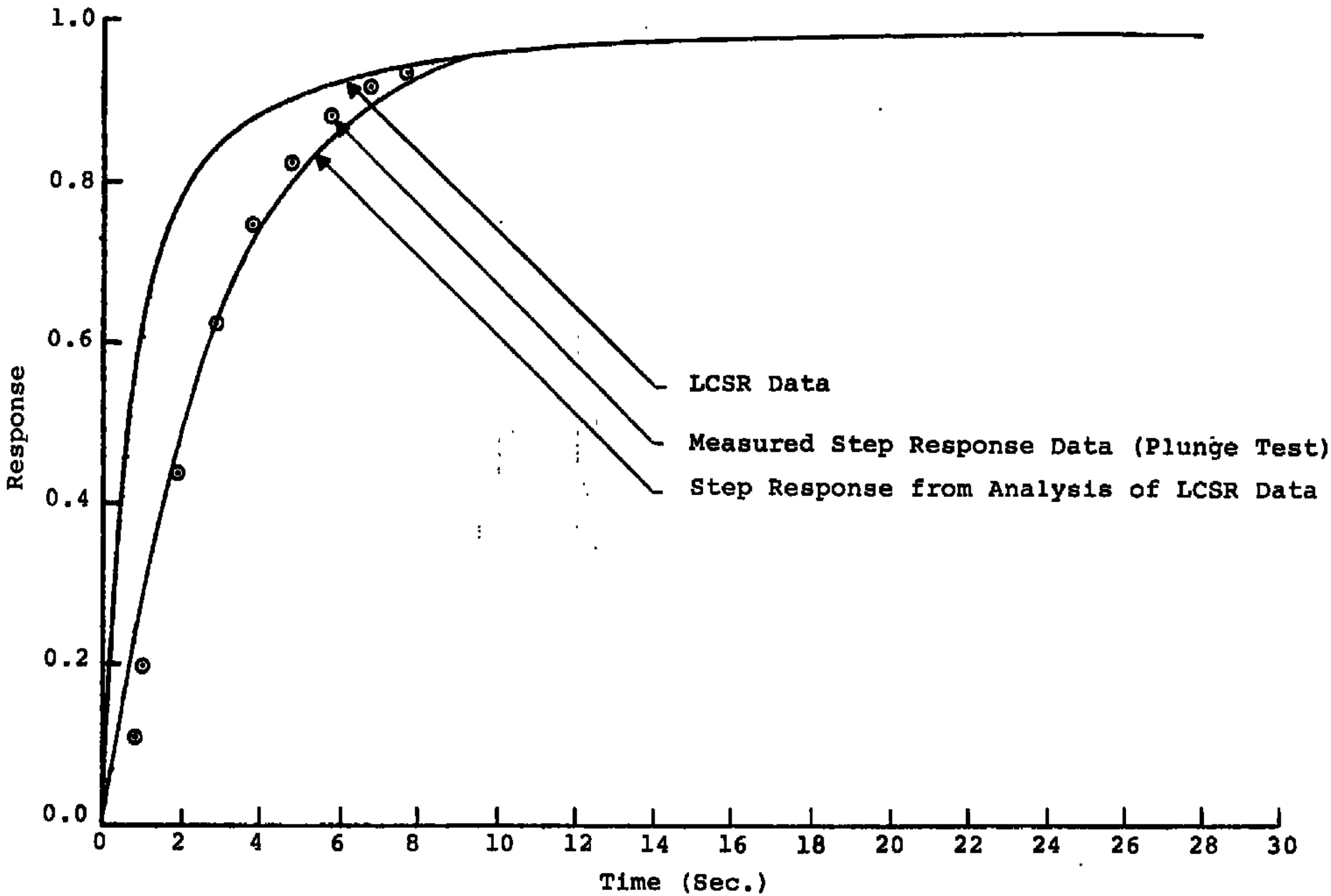


Figure 6.14: LCSR Raw Data and Step Response from Plunge Test and LCSR Analysis.

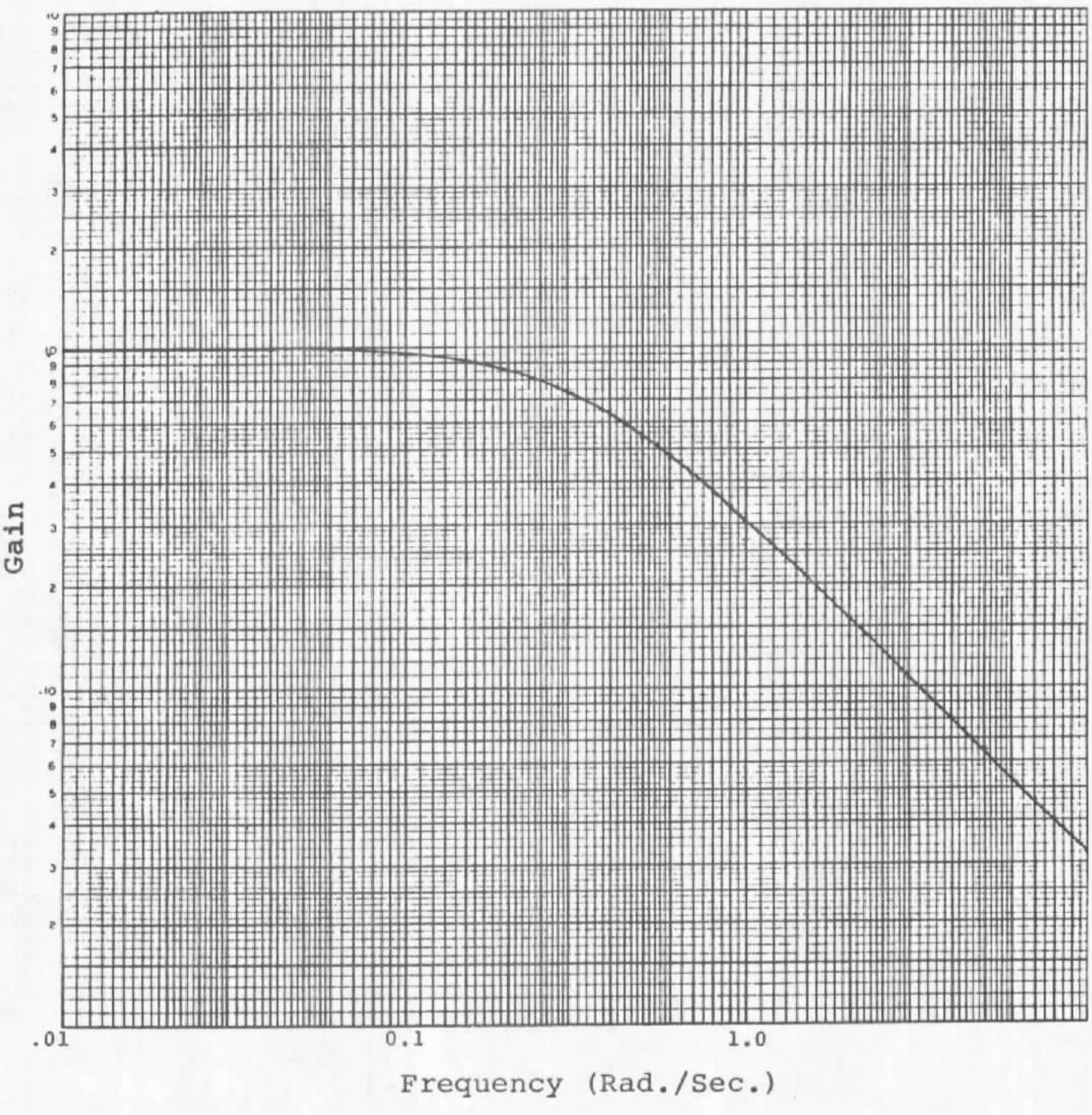
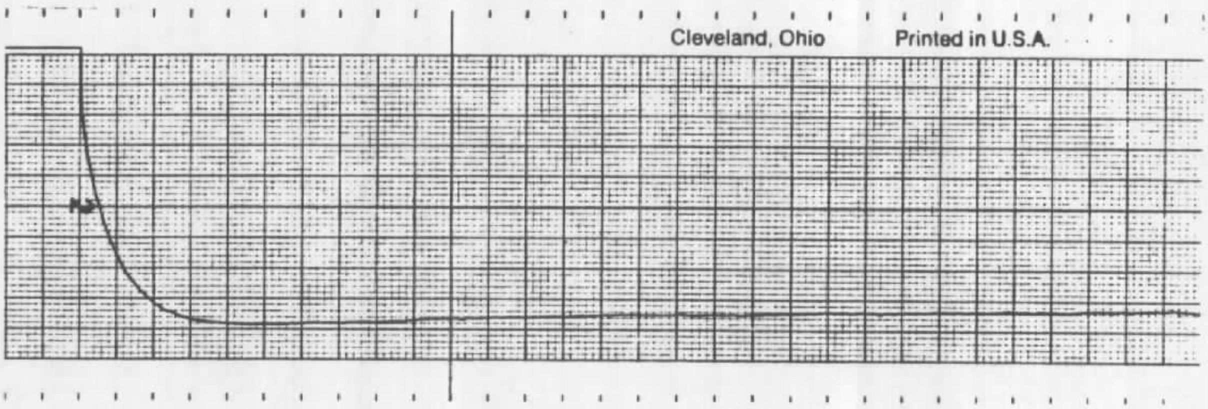
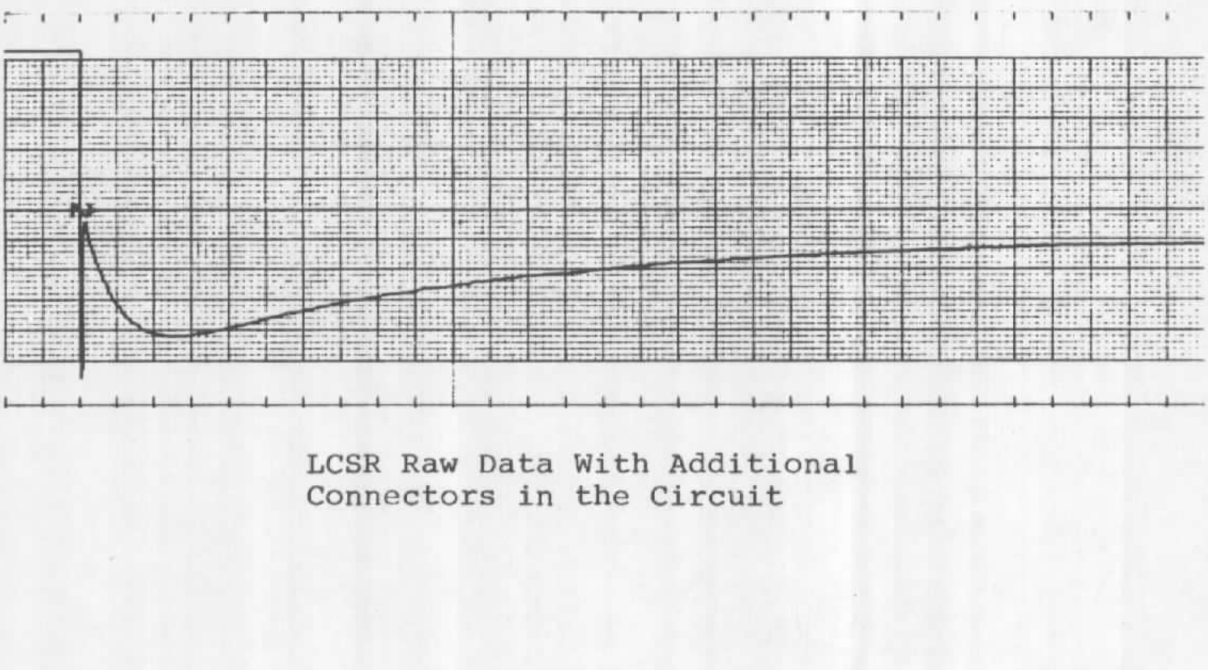


Figure 6.15: Frequency Response of a Thermocouple (Type E, ID E-T, 3FPS Water).



LCSR Raw Data Without Additional
Connectors in the Circuit



LCSR Raw Data With Additional
Connectors in the Circuit

Figure 6.16: Effect of Thermocouple Connectors on LCSR Raw Data.

inhomogeneities in the connectors, the LCSR data contain emf components that are not related to the temperature changes at the measuring junction.

6.8. Flow Characterization

Since the use of thermocouples in gas turbines involves ambient conditions which are difficult or impossible to match in laboratory response time testing, it is important to improve pre-installation response time estimation. It has been shown[6] that two constants, C_1 and C_2, are required to characterize temperature sensors:

$$\tau = C_1 + C_2/h \tag{6.1}$$

where

τ = time constant

h = surface heat transfer coefficient

Consequently, if C_1 and C_2 can be determined experimentally, then the time constant can be estimated for the sensor in any medium for which the heat transfer coefficient can be estimated.

Experimental evaluation of C_1 and C_2 involves the following steps:

1. Perform plunge tests in a fluid (or fluids) at several flow rates to obtain time constants.
2. Use available heat transfer correlations to evaluate h at each flow condition.

3. Fit Equation 6.1 to the data from steps 1 and 2 to provide C_1 to C_2.

This procedure was used to characterize two thermocouples used in this project. The response versus flow data were collected in the water system. A least square fit was performed on the data to identify Equation 6.1 for each thermocouple. The equations were then used to estimate time constants in flowing air. These estimates were compared with the time constants measured by plunge tests in flowing air. The results are shown in Table 6.6.

Equation 6.1 and the response versus flow data were also used to demonstrate the effect of water flow rate on response time of a type J thermocouple. The results are shown in Figure 6.17.

As shown in Table 6.6, the agreement between the measured values and the values estimated from the equations are reasonable. Therefore, it is possible to perform pre-installation laboratory test and analysis to obtain response time estimates at process conditions. This is a useful tool for selecting temperature sensors that must meet certain in-service response time requirements. In addition to the effect of flow, the equations can be used in conjunction with heat transfer analysis to estimate the effect of temperature on response time.

Table 6.6

Validation of Response Versus Flow Correlations for Thermocouples

Thermocouple			Time Constant (sec.)	
Type	I.D.	Test Condition	Measured	Estimated
J	J-T	Air at 16 m/sec.	14.8	11.2
K	K-T	Air at 16 m/sec.	15.0	12.1

NOTE: The complete specification of each thermocouple is found in Appendix A with the I.D. given in this table.

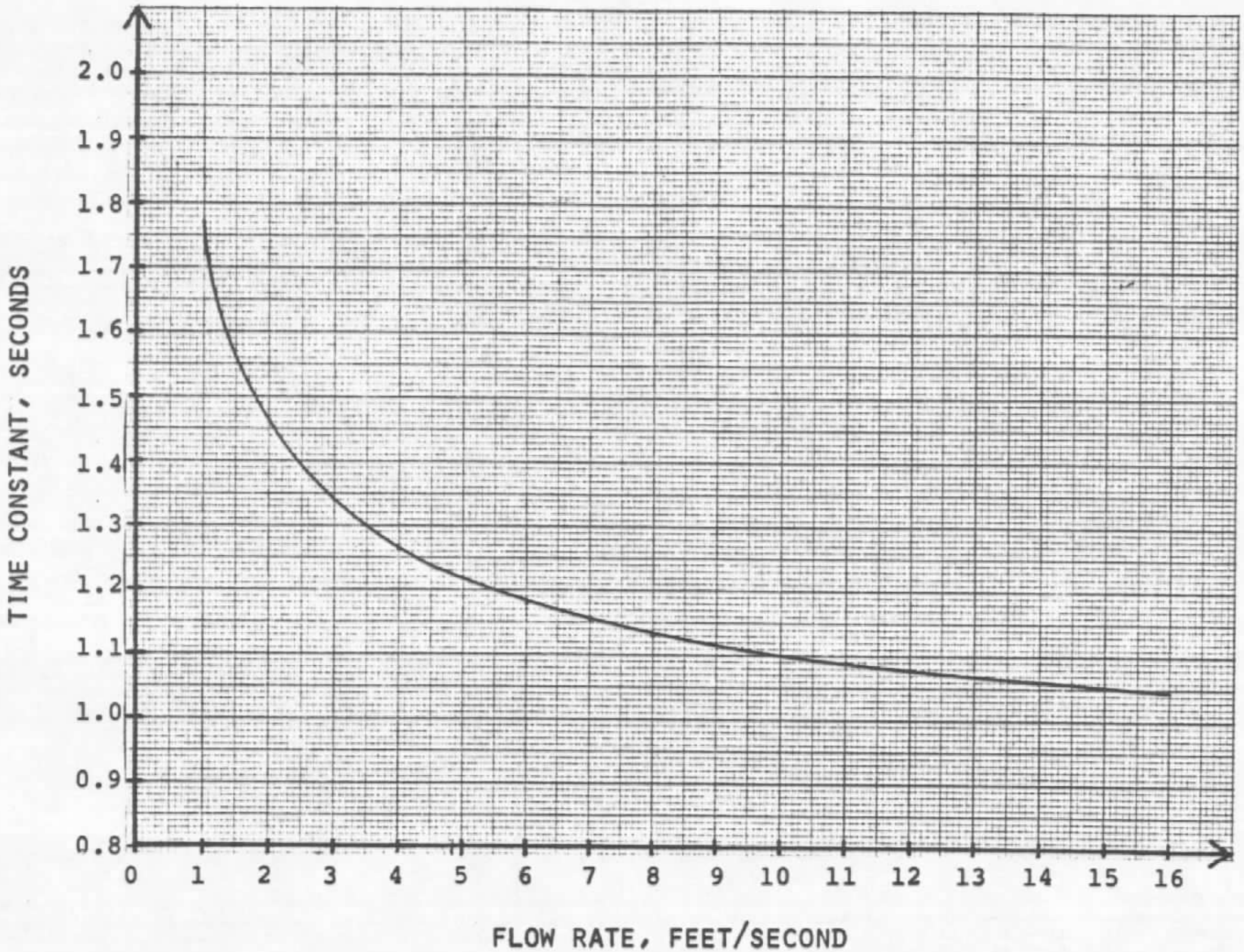


Figure 6.17: Response vs. Flow

6.9. Electrical Hazard

LCSR tests on thermocouples involve voltages of up to 80V (AC or DC) from power supplies which can deliver up to 6 amps. Protection from electrical shock is achieved by prohibiting contact with bare wires at the LCSR instrument connectors. However, protection from contact with the wires in the thermocouple circuit itself must depend on insulation on these wires. Further work is needed on additional improvements in signal processing so as to allow smaller heating currents.

7. DISCUSSION OF RESULTS

The work performed here has clearly shown the validity of LCSR testing for thermocouples of type J, K, E and T. Also, improvements in test equipment design have been demonstrated. As a result of this, capability for LCSR testing of thermocouples has been brought to the level that existed for platinum resistance thermometers seven or eight years ago when it came into routine use for that type of sensor in nuclear power plants.

Because thermocouples are used in a wide variety of style and configurations, additional testing is required to determine test adequacy of those styles and configurations (especially bare thermocouples attached directly to metallic objects). In addition, the lessons learned in laboratory testing using prototype equipment should be implanted in developing a commercial instrument for use by semi-skilled workers.

8. PHASE II EFFORT

The excellent results obtained in the Phase I effort suggest that a Phase II effort is justified and should be pursued. The prior experience with developing practical industrial technology for LCSR testing of resistance thermometers provides a good model for a similar effort for thermocouples. The Phase II project should involve three main activities:

1. Complete evaluations for all common thermocouple types and configurations.
2. Build a commercial instrument based on lessons learned with the prototype.
3. Carry out an extensive field test program on sensors installed in operating processes and resolve any procedural or equipment problems which arise here that did not appear in laboratory testing.

9. CONCLUSIONS

The project objectives were fulfilled by experimental verification of the LCSR method for type J, K, E or T thermocouples and by development of the equipment with capabilities required for testing. In-situ response time test accuracy of about 20 percent is now achievable. This is possible because of refinements developed for the instrumentation and the signal processing methods.

The success of this project permits commercial development of instrumentation for routine testing by technician-level workers. This commercial development will satisfy other industry and military needs in addition to the specific Air Force requirments which stimulated this work.

This work is viewed as a part of the new thrust in sensor technology to develop SMART sensors. The ultimate SMART sensor will include self-diagnosis of existing or incipient faults and self-calibration. The LCSR test will provide part of the SMARTNESS built into instruments of the 1990's.

REFERENCES

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5. H. M. Hashemian and T. W. Kerlin, "Experience with RTD Response Time Testing in Nuclear Plants," Proceedings of The Industrial Temperature Measurement Symposium, September 10-12, 1984.

6. T. W. Kerlin, R. L. Shepard, H. M. Hashemian and K. M. Petersen, "Response of Installed Temperature Sensors," Temperature Its Measurement and Control in Science and Industry, Volume 5, American Institute of Physics, 1982.

Appendix A

Description of Thermocouples For This Project

Table A.1

Listing of Sheathed Thermocouples for This Project

Item	Type	Description	Model No.	I.D.
1	J	Transition	TJ36-ICSS-316U-12	J-T
2	K	Transition	TJ36-CASS-316U-12	K-T
3	E	Transition	TJ36-CXSS-316U-12	E-T
4	J	Quick Disconnect	ICSS-316U-12	J-Q
5	K	Quick Disconnect	CASS-316U-12	K-Q
6	E	Quick Disconnect	CXSS-316U-12	E-Q
7	T	Transition	TJ36-CPSS-316U-12	T-T
8	T	Quick Disconnect	CPSS-316U-12	T-Q

Above are 3/16 inch, ungrounded junction, 304 S.S. sheathed thermocouples made by Omega Engineering.

The I.D. given in this table was designated by AMS to facilitate reference to these thermocouples in the report.

Table A.2

Listing of Exposed Junction Thermocouples for This Project

Item	Type	Junction Style*	I.D.
1	J	Twisted and Silver Soldered	J-TSS
2	J	Lap Welded	J-LW
3	J	Lap and Silver Soldered	J-LSS
4	J	Butt Welded	J-BW
1	K	Twisted and Silver Soldered	K-TSS
2	K	Lap Welded	K-LW
3	K	Lap and Silver Soldered	K-LSS
4	K	Butt Welded	K-BW
1	T	Twisted and Silver Soldered	T-TSS
2	T	Lap Welded	T-LW
3	T	Lap and Silver Soldered	T-LSS
4	T	Butt Welded	T-BW

* See Figure A.1 at the end of this chapter.

Above were made with thermocouple wires purchased from Omega Engineering.

The I.D. given in this table was designated by AMS to facilitate reference to these thermocouples in the report.

Table A.3

Thermocouple Wires Used in This Project

Item	Type	Model No.
1	K	TT-K-24
2	J	TT-J-24
3	E	TT-E-24
4	J	EXPP-J-20S
5	T	EXPP-T-20S
6	K	EXPP-K-20S

Items 1 to 3 are 24 Gauge, Teflon Insulated, solid wires.

Items 4 to 6 are 20 Gauge, Polyvinyl Insulated, stranded wires.

The wires were purchased from Omega Engineering.

Table A.4

Description of Thermocouple Types Used in This Project

Type	Description
J	Iron/Constantan
E	Chromel/Constantan
K	Chromel/Alumel
T	Copper/Constantan

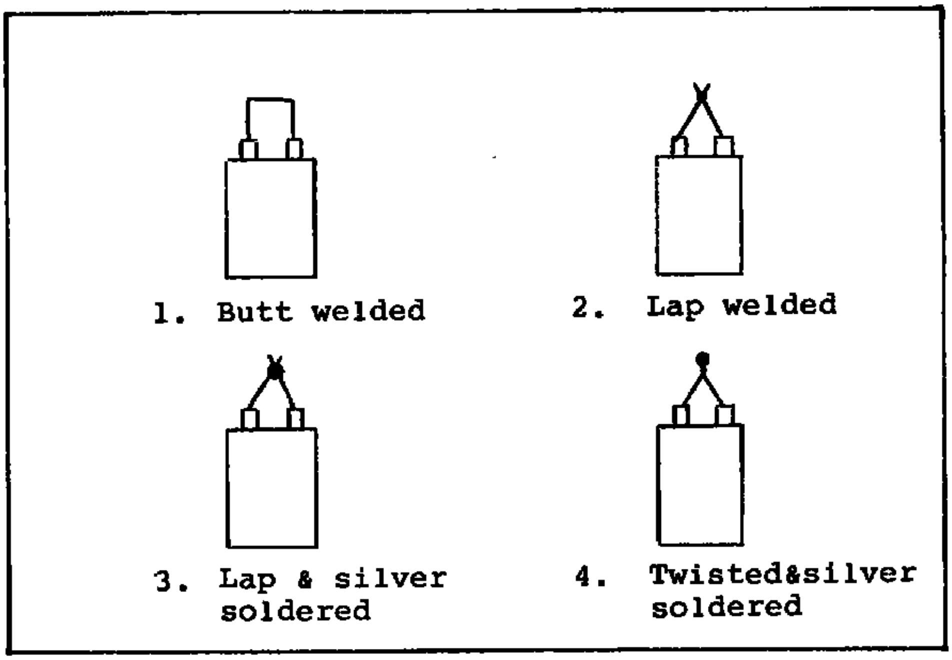

Figure A.1: Junction Style for Exposed Thermocouples Used in this project.